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Environmental Measurements, Inc, San Francisco, CA

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Accuracy of Remotely Sensed SO_2 Mass Emission Rates

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ABSTRACT

Remote sensing data of single-track power plant emissions and local wind speed have been analyzed to determined SO_2 mass flux for comparison with EPA referenced methods. Four days of SO_2 data were gathered from a moving platform by three upward-viewing remote sensors -- two ultraviolet absorption spectrometers and an infrared gas filter spectrometer. Wind velocity data were gathered by a laser-doppler velocimeter (LDV); supplemental data were obtained from a tethered balloon (telemetered) and pilot balloons (optical theodolite). The data matrix (SO_2, X-Y position, wind velocity for 120 traverses) was computer processed; the end result was the SO_2 mass flux derived from the remote sensing data. Comparisons were made between these SO_2 fluxes (averages for 20 minutes and 60 minutes) and those derived from in-stack measurements. The results of the comparisons show the relative accuracy of the remote sensing technique for quantifying SO_2 mass emission rates. The analysis shows that as averaging time increases from 20 minutes to 12 hours the difference between the remotely measured SO_2 mass flux and the stack sampling SO_2 mass flux decreases from about ±35% to ±10%. In general, no single wind measuring system produced superior results over the other two. The LDV and COSPEC, however, produced the best agreement with Method 6 (+6%) when the plume was transported near the LDV instrument.

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SECTION 1

INTRODUCTION

BACKGROUND

Environmental Measurements, Inc. (EMI) collected air quality data with three remote sensing spectrometers at a southwestern U.S. coal-fired power plant using a moving instrument platform and an automated data acquisition system. The instruments were:

- COSPEC III
- COSPEC II
- Gas-Filter Correlation Spectrometer

The measurements were made over a five-day period, 2-6 August, 1976, to gather upward-looking SO_2 data to be used to evaluate the relative accuracy of the instruments for determining mass emissions rates remotely.

Concurrent wind measurements were made with three systems:

- Laser Doppler Velocimeter (LDV), Lockheed Missles and Spacecraft Corporation[4]
- Tethersonde (TS), Intera, Inc.[5]
- Pilot balloons (PB), EMI.[1]

Simultaneous in-stack reference method testing of SO_2 concentrations EPA (Method 6) and gas velocity EPA (Method 2) were made by Entropy Environmentalists, Inc.[3]

The data collected from the moving laboratory have been reported in tabular and plotted formats.[1] These listings provided the spatial SO_2 data needed to combine with the wind velocity profile data for calculating SO_2 mass emission rates.

PURPOSE

All of the field data have been synthesized into a three-by-four SO_2 mass flux matrix: mass emission rates from *three* remote sensing spectrometers for *four* sets of wind measurements. These

remotely quantified SO_2 fluxes were compared with reference method in-stack measurements to determine the:

- Relative accuracy of the remote sensing method as compared to the reference method, and
- Improvements, if any, in remote sensing accuracy using more accurate measuring equipment.

SECTION 2

SUMMARY

EQUIPMENT

The data analyzed in this report were gathered by three remote sensing spectrometers and three different wind measuring systems.

Spectrometers

Two of the spectrometers were Barringer Research Ltd. correlation spectrometers: COSPEC III (serial number 6061) and COSPEC II (serial number 5922) were provided by EMI and U.S. EPA/RTP, respectively. The third instrument was a government-provided gas-filter correlation spectrometer built by Science Applications, Inc. All three instruments were installed in an EMI Air Quality Moving Laboratory in the upward-viewing mode.

Wind Measurements

Three different wind measuring systems were used to determine wind velocities at the altitude of the stack emissions:

- The van-mounted Laser Doppler Velocimeter (LDV) system was located 800 meters northwest of the stack. From this location it collected and analyzed horizontal and vertical remote wind velocity data at altitudes from 30 meters to 800 meters above ground level (AGL). The data were recorded on strip charts and on magnetic tape for later analysis.

- A tethered balloon system located 100 meters from the LDV site was used to measure wind velocity from ground level to a height of 600 meters. The data were recorded on strip charts for later analysis.

- Pilot balloons were released from the tethersonde site; the data were analyzed to determine wind velocity up to 1000 meters AGL.

All data have been reported separately by the individual contractors.[1,3,4,5]

MEASUREMENTS

The equipment provided the following sets of measurements:

- 120 traverses with the moving laboratory
- 13 hours of vertical wind profile data from the LDV
- 20 hours of vertical wind profile data from the tethersonde
- 20 pilot balloon measurements of winds aloft

Figure 1 illustrates the field measurement activities, and Figure 2 shows the traverse routes used by the moving laboratory and the sites of the meteorlogical systems.

Figure 1. Field activities (clockwise from lower right): Adding liquid nitrogen to GFC Spectrometer; pair of upward-looking COSPEC remote sensors; observing flight of pibal toward tethered balloon; checking MAP listing of van position and spectrometer SO_2 data.

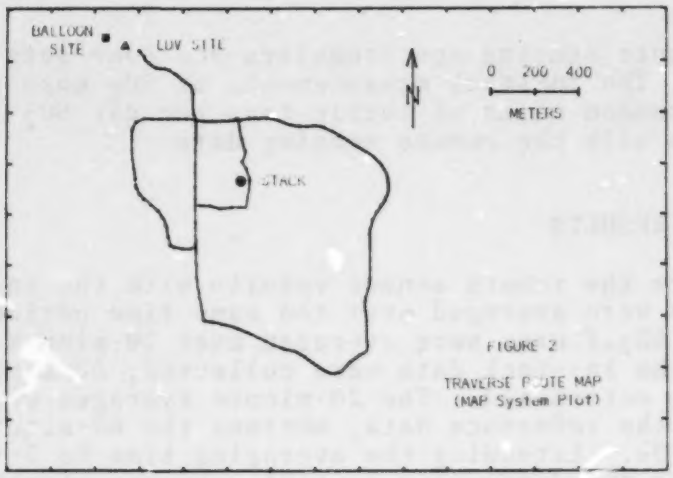

Figure 2. Traverse route map

DATA PROCESSING

All the field data prepared by EMI and other contractors were reviewed and integrated into a single data matrix.

Remote Sensor Data

The SO_2 optical depth data for the three spectrometers were edited, and appropriate calibration factors were applied to convert the millivolt reading to part-per-million-meters SO_2 (ppmM SO_2). The X-Y coordinates of the moving laboratory were also edited to establish the same coordinates system for all 120 traverses. The final coordinates and SO_2 optical depth data were stored into a computer for the computation of SO_2 mass emission rates.

Wind Data

The LDV system wind data were reviewed; discrepancies were noted between the tabular listings and the plotted results. It was determined that the data had been hand-processed and could contain a systematic error of +10% (the difference between hand-processed *peak* values and machine-processed *average* values). A second processing by computer was requested. This computer processing resulted in a new set of LDV wind velocity numbers. Rather than to present both sets of numbers, it was decided to present only the revised LDV values. The original data (LDV) were computer-processed to form an LDV' set, which was used as delivered.

RESULTS

The processed data were used to calculate SO_2 mass emission rates yielding a three-by-four matrix: SO_2 mass emission rates

from *three* remote sensing spectrometers for *four* sets of wind measurements. The in-stack measurements of SO_2 mass flux were converted to common units of metric tons per day SO_2 (MT/D SO_2) for comparison with the remote sensing data.

COMPARISON of RESULTS

To compare the remote sensor results with the in-stack results all data were averaged over the same time periods. The remote sensor SO_2 fluxes were averaged over 20-minute periods during which the in-stack data were collected; 60-minute averages were also determined. The 20-minute averages were within about ±35% of the reference data, whereas the 60-minute averages were within ±20%. Extending the averaging time to 7-to-12 hours further narrows the difference to ±10%, showing clearly that the relative accuracy of the remote sensing method is dependent on the averaging time or, more precisely, the number of profiles used in an average. There was no significantly superior wind measuring system, considering the time-averaged comparison of results. The pibal-derived SO_2 fluxes, however, were closer to the reference method than were either the LDV' or the tethersonde results for 20-minute averaged data.

SECTION 3

CONCLUSIONS and RECOMMENDATIONS

CONCLUSIONS

The following conclusions can be drawn from the first-order analysis presented in Section 6 of this report regarding the relative accuracy of the remote sensor flux calculations:

SO_2 Flux Accuracy

The relative accuracy of the SO_2 mass flux calculations using remote sensor and wind speed data is dependent on the averaging time or number of profiles. The approximate differences relative to reference methods are:

- ±35% for 20-minute averages or 2-to-5 traverses
- ±20% for 60-minute averages or 4-to-13 traverses
- ±10% for 7-to-12 hour averages or 25-to-75 traverses

These results are consistent with previous studies. Single measurements of a plume profile can have greater than ±50% error because under most dispersion conditions the actual plume cross-section is non-uniform, and several measurements (traverses are required to provide a representative average profile. The greater the number of traverses, the lower the expected error until the minimum difference (±10% in the case of these data) is approached.*

Wind Measurement Accuracy

The relative accuracy of the three sets of wind speed data, as shown in the individual sets of SO_2 mass flux calculations, can be assessed as follows:

---

*Millán M. Millán, in his research for Atmospheric Environmental Service of Canada, notes that their average for 18 to 22 profiles/hour at ≈1.5 km downwind is about ±15-17% different, which agrees reasonably well with this data.

LDV' --

The reprocessed LDV' data corrected the positive bias of the original LDV data. Overall, the LDV' average mass flow (78.9MT/D) was 17% greater than the average Method 6 determination (67.4MT/D). However, selecting data associated with SE winds that brought the plume over the LDV site and using only the Method 6 results for the same time frame, the LDV' results with COSPEC III are only 6% higher than the average for Method 6 (70.1 vs 66.2).

TS --

The tethersonde data had a negative bias producing fluxes over the long term within -10% of the reference method.

PB --

The pibal data produced the best results (<±5% in the long term), but the number of 20-minute averages was smaller than the other two methods.

It appears that the LDV system may be the most accurate of the systems tested, provided that it is used near the plume to measure the wind field near or in the plume. This finding from the subset of SE winds implies that a mobile remote wind monitoring system would be desirable for remote sensor plume studies.

RECOMMENDATIONS

The following recommendations are offered to assist in advancing the state-of-the-art of remote sensing emissions monitoring:

Further Analysis

Further analysis of the body of data in this report could lead to:

- Interpretation of the relative accuracy of remote sensor SO_2 mass fluxes expressed in terms of error intervals and confidence limits.
- Comparison of these data (1976) with previous similar data (1975) to determine how to optimize remote SO_2 mass flux measurements.
- Identification of measurement protocols that should be followed to minimize the error in the flux calculation and conditions that should be avoided that degrade the measurement technique.
- Selection of the most suitable wind velocity measurement system to accompany remote sensor measurements used for emission rate calculations.

Further Testing

With or without further analysis, further field testing could lead to:

- Confirmation of measurement conditions that tend to optimize the flux calculation.
- Verification of the most suitable wind velocity measurement system for remote sensor field work, such as a mobile remote wind sensing system to operate in conjunction with a remote sensor team.

SECTION 4

DATA PROCESSING

The first step in processing the remote sensor and supporting data was to prepare an activity summary relating all sets of measurements in time. Figure 3 shows the times for every field measurement.

Each set of data was reviewed for the four measurement days to determine its suitability for further analysis. The three sets of wind data were reviewed independently; the three spectrometer data sets were individually prepared for merging with the wind data to calculate SO_2 mass flux. For each of the 414 flux calculations a plume profile was drawn to aid in the analysis.

WIND SPEED DATA

Before wind speed figures could be selected from the various data sets for the individual *times* of the remote sensor traverses, the individual *altitudes* first had to be selected. This was done by calculating plume rise and vertical dispersion; the appropriate wind speeds within the plume were then taken from the vertical wind profiles.

Plume Height

The extensive wind information could not increase the accuracy of the flux calculations unless the height of the plume was known. If the wind speed varied considerably with altitude, it was imperative to know the height of the plume because the flux calculation results are directly proportional to the wind speed. A 20% error in wind speed causes a 20% error in the flux calculation.

To obtain an approximate plume height (since no direct measurements were made) the existing wind information was used in conjunction with the Briggs plume rise formula. (Though its agreement with a wide range of plumes is established[6], its use during unstable conditions such as those of these tests is not so well established.)

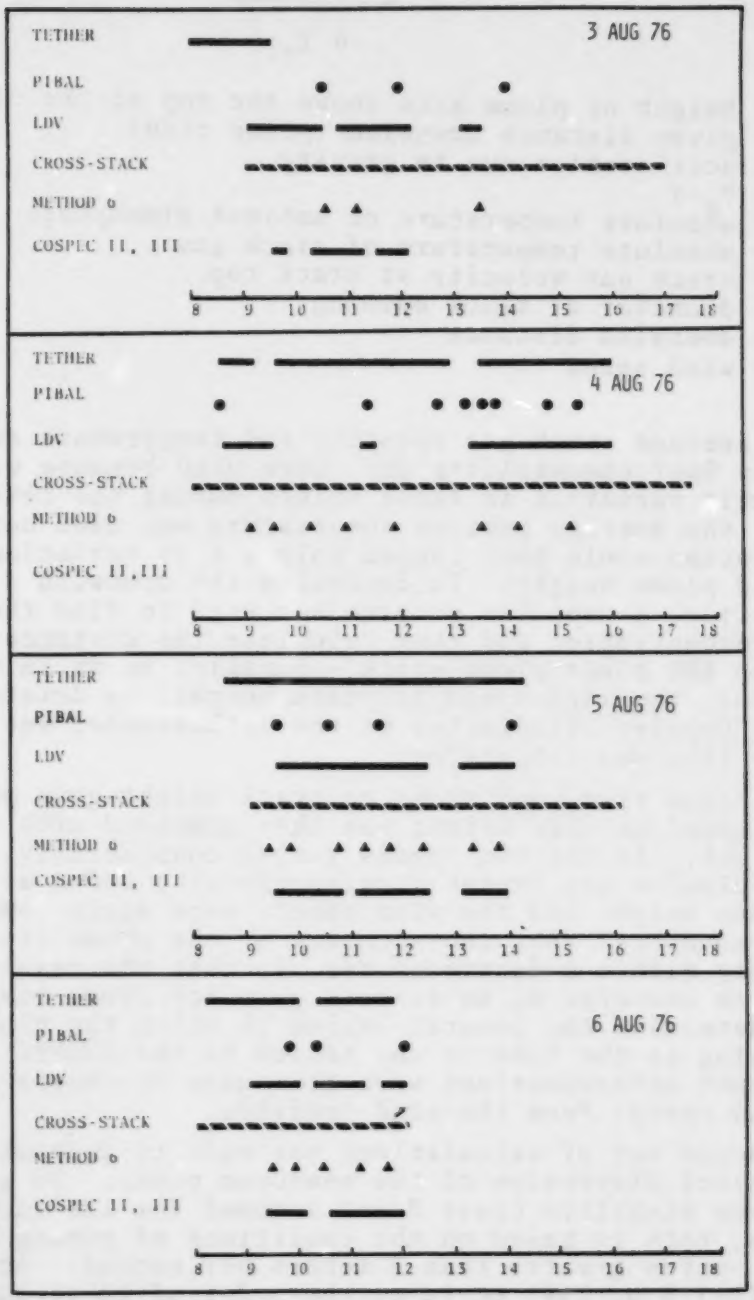

Figure 3. Activity Summary.

$$\Delta h = 2.0\, F^{1/3}\, \chi^{2/3}\, \upsilon$$

where

$$F = \frac{g\, \Delta T\, V_s\, d^2}{4\, T_s}$$

Δh = height of plume axis above the top of the stack at given distance downwind (plume rise)
g = acceleration due to gravity
$\Delta T = T_s - T$
T = absolute temperature of ambient atmosphere
T_s = absolute temperature of stack gas
V_s = stack gas velocity at stack top
d = diameter of stack opening
χ = downwind distance
υ = wind speed

The average stack gas velocity and temperature as measured by Entropy Environmentalists Inc. were used because of a relatively small variation in these values during the test period. Likewise, the average ambient temperature was used because the 14°K variation would have caused only a ± 1% variation in the calculated plume height. To determine the downwind distance of each traverse, a computer program was used to find the point of maximum concentration and then calculate the distance of that point from the power plant stack. Finally, as an initial wind speed input, the wind speed at stack height, as determined by the Laser Doppler Velocimeter or the Tethersonde, was input and the plume rise was calculated.

The plume rise when added to stack height gave plume height. The wind speed at this height was then compared with the speed at stack height. If the two speeds varied considerably, the plume rise calculation was repeated using the wind speed at the calculated plume height and the wind speeds were again compared. It must be remembered that the accuracy of the plume rise calculations is probably within a factor of two, so that the results were not expected to converge on an exact figure for plume rise, but were used to determine the general region in which the plume was likely to be moving at the time it was sensed by the COSPEC and GFC. These height determinations were then used to choose the appropriate wind speeds from the wind profiles.

A second set of calculations was made to determine the probable vertical dispersion of the measured plume. To generalize the process Stability Class B was assumed for all four measurement days; this is based on the conditions of strong insolation and wind speeds greater than 3 meters per second. According to Gifford (Ref.6,p. 259) σ_z is on the order of 20-to-30 meters at 200-to-300 meters downwind of the stack. These assumptions were all reasonable for the typical plume measurement made with the

moving laboratory. Hence a 6σ vertical plume dispersion of ±75 meters, centered on the plume height calculated previously, was used for selecting wind speeds. For example, if the calculated plume height was 200 meters, wind speed data from 125 to 275 meters altitude above ground level would be selected for that traverse.

Each set of wind data was studied in turn, starting with the LDV data.

LDV

The laser Doppler Velocimeter wind speed data were originally presented tabularly for vertical sweeps to 80 meters altitude and for temporal measurements made at fixed altitudes for periods of 30 seconds. Selected data were also plotted with time. Comparison of the tabular and plotted velocity data revealed some discrepancies -- differences of up to 30%.

Rather than completely discarding the original data, both sets were retained for the purpose of Table 1 and identified as follows:

- LDV - original hand-processed results decreased by 10% to approximate the averages produced by computer processing.
- LDV' - new computer-reprocessed results. (For 3 August LDV' could not be computed because the full set of necessary data was either not available or not adequate for this calculation.)

From the LDV' data wind speeds within the plume (plume height ±75 meters) were selected that were coincident with the traverse time recorded by the moving laboratory. Where two or three values were available, they were averaged; in many cases only one value existed.

All wind speeds are summarized in Table 1. If there were no data at the proper altitude the nearest-altitude wind speed was selected and coded "*a*". Also, if there were no data within the time limits the nearest-time wind speed was selected and coded "*b*". (See Section 5 for further discussion of these Error Codes.)

Tethersonde

The same criteria were applied to the tethersonde data, and the best wind speed values were chosen and tabulated. (See Table 1.) Over half of the tethersonde measurements were made at altitudes lower than the caculated plume; they are coded "*a*". None were out of tolerance with respect to time.

Pibal

The twenty pilot balloon measurements were treated similarly. However, the selected pibal wind (all of which were in tolerance for altitude) were purposely applied to adjacent time intervals to simulate the situation often necessitated by extrapolating infrequent pibal measurements. They are coded "*b*" in Table 1.

Wind Summary

The selected wind data presented in Table 1 are also plotted in Figure 4. These daily plots show the differences between the four sets of velocities. It is important to note:

- The differences between the LDV and LDV' wind data are significant; the LDV results tend to be higher by as much as 30%, so they were not used for final computation.
- The tethersonde data tend to be low, principally because the balloon was often tethered at altitudes below plume heights determined after the field project.
- The pibal data show general agreement with other results.

REMOTE SENSOR DATA

The remote sensor SO_2 optical depth data required further processing prior to merging with the wind data (in the flux calculations). The COSPEC and GFC were treated in a consistent fashion.

COSPEC

When making mass flux calculations using COSPEC (or GFC) measurements, it is imperative to accurately determine a zero reference (background) level, which is subtracted from the COSPEC (or GFC) values, thereby leaving only a signal due to the SO_2 of the measured plume. In working with digital results (which are averages over 20 meters, as provided by the MAP System), it is difficult to spot a background value such as might be done by drawing a baseline on a chart record output; therefore, a different technique was used.

Most traverses under the plume were made so that there were five to ten 20-meter averages on either side of the plume that were measurements of background levels. Each traverse was evaluated, and an average of five readings in the background region on either side of the plume was calculated to provide an average background. If the average background on one side was more than six

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TABLE 1. WIND SPEED SUMMARY

TRAV-ERSE NO.	TIME (MDT)	STACK DIST. (M)	PLUME HEIGHT (M)	LOV			LOV'			TETHERSONDE			PIBAL		
				TIME (MDT)	HEIGHT (M)	SPEED (M/S)	TIME (MDT)	HEIGHT (M)	SPEED (M/S)	TIME (MDT)	HEIGHT (M)	SPEED (M/S)	TIME (MDT)	HEIGHT (M)	SPEED (M/S)
	3 AUG 76														
1	0929-0933	214	171	0929-0933	150-200	10.7				0925	234	6.3			
2	0936-0941	213	174	0939-0941	182	9.6									
3	1020-1024	204	183	1020-1024	121	8.4							1031	97-202	7.7
4	1026-1029	213	193	1026-1029	121	7.7							1031	97-202	7.7
5	1032-1035	214	189	1030	121	8.0									
6	1047-1049	241	187	1047-1049	121	7.8									
7	1057-1102	279	185	1057-1102	121	7.5									
8	1103-1108	288	208	1103-1108	121	7.6									
9	1109-1112	285	231	1109-1112	121	6.2									
10	1139-1142	526	289	1145	300	8.6									
11	1143-1146	288	235	1145-1146	200-300	8.5									
12	1147-1150	285	215	1149	150-200	8.6									
13	1157-1159	238	210	1204	200	11.9							1201	97-202	5.0
14	1159-1204	278	218	1204	200	11.9									
	4 AUG 76														
15	0856-0901	201	210	0856-0900	150-200	5.9				0856-0900	203	5.4			
16	0904-0908	220	206	0904-0908	150-200	6.8				0904-0908	234	5.5			
17	0908-0913	207	204	0908-0912	150-200	5.4				0908-0909	234	5.3			
18	0913-0916	210	208	0916	150-200	6.1									
19	0917-0920	213	213	0920	150-200	5.8									
20	0925-0929	213	210	0928	150-200	6.0									
21	0931-0934	217	227	0932-0933	150-300	5.7				0938	20a	6.2			
22	0935-0938	220	211	0932	150-200	5.7				0942	112	5.4			
23	0938-0942	210	208	0932	150-200	5.7				0954-0959	142	4.4			
24	0954-0959	226	212							1001-1003	173	4.2			
25	1001-1003	216	220							1007-1010	173	3.6			
26	1007-1010	532	300							1011-1015	165	3.1			
27	1011-1015	502	292							1016-1022	153	3.6			
28	1016-1022	415	272							1022-1027	163	3.8			
29	1022-1027	455	282							1029-1034	142	3.8			
30	1029-1034	539	325							1034-1038	152	3.1			
31	1034-1038	550	328							1038-1042	142	3.0			
32	1038-1042	518	319							1047-1051	142	4.0			
33	1047-1051	511	317							1052-1055	142	4.0			
34	1052-1055	481	310							1055-1059	142	3.7			
35	1055-1059	543	321							1138-1141	142	3.1			
36	1138-1141	257	229	1123-1124	150-300	5.9				1141-1146	142	3.0			
37	1141-1146	245	225	1123-1124	150-300	5.9				1149-1154	142	2.5			
38	1149-1154	308	241	1149-1154	149	4.3				1158-1204	112	3.5			
39	1158-1204	277	234	1158-1204	149	4.6				1247-1251	81	2.9			
40	1247-1251	280	235							1257	81	3.4			
41	1257-1304	260	229												

(continued)

TABLE 1 (continued)

TRAV-ERSE NO.	TIME (MDT)	STACK DIST. (M)	PLUME HEIGHT (M)	LOV			LOV'			TETHERSONDE			PIBAL		
				TIME (MDT)	HEIGHT (M)	SPEED (M/S)	TIME (MDT)	HEIGHT (M)	SPEED (M/S)	TIME (MDT)	HEIGHT (M)	SPEED (M/S)	TIME (MDT)	HEIGHT (M)	SPEED (M/S)
42	1305-1310	245	225										1311	97-202	5.5
43	1316-1321	262	210		150	4.9	1320	150-200	6.1						
44	1321-1328	232	253	1327	150	4.9	1327	150	4.8	1325-1328	96	1.8			
45	1330-1336	259	208	1327-1325	150	6.2	1331-1335	150-200	4.5	1330-1336	81	3.5	1331	97-202	3.2
46	1338-1341	280	229	1339-1340	150-300	6.1	1338-1339	150-300	6.4	1338-1341	81	2.8			
47	1342-1347	295	222	1345-1346	150-300	6.5	1342-1347	150-300	4.7	1342-1347	95	3.8			
48	1348-1354	253	208	1349-1350	150-300	6.9	1349-1350	150-200	6.0	1348-1354	112	2.1	1351	97-202	5.4
49	1444-1448	276	250	1445-1446	200-300	5.2	1444	200-300	3.6	1444-1448	66	1.4			
50	1449-1452	285	262	1449-1450	200-300	5.0	1451	200-300	4.2	1449-1452	51	4.1	1451	97-306	3.3
51	1452-1456	312	264	1453-1454	200-300	4.3	1455	200-300	5.3	1452-1456	51	3.8			
52	1456-1501	259	234	1457-1458	200-300	5.8	1459	200	5.5	1456-1501	81	2.5			
53	1501-1506	296	222	1501-1506	150-300	7.1	1502-1507	150-300	5.7	1501-1505	81	3.2			
54	1506-1512	281	234	1509-1510	200-300	7.1	1506-1510	200-300	7.1						
55	1533-1538	444	251	1533-1538	200-300	6.7	1532-1537	200-300	4.7						
56	1538-1543	392	236	1538-1542	200-300	6.6	1540	200-300	4.3						
	5 Aug 76														
57	0924-0930	202	230	0926-0930	200-300	5.1	0927-0928	200-300	4.4	0924-0930	234	5.2			
58	0932-0937	227	236	0934-0935	200-300	5.2	0931-0935	200-300	4.2	0932-0937	234	4.7	0936	97-306	4.4
59	0937-0941	206	235	0938-0939	200-300	4.3	0938-0939	200-300	3.9	0937-0941	234	5.0			
60	0941-0948	222	239	0942-0943	200-300	4.3	0942-0946	200-300	3.9	0941-0948	234	4.5			
61	0948-0952	201	243	0950-0951	200-300	4.6	0950	200-300	3.8	0948-0952	234	4.0			
62	0952-0957	214	226	0954-0955	150-300	5.2	0953-0954	150-300	4.9	0952-0957	234	4.1			
63	1000-1004	205	237	1003-1004	200-300	3.7	0959	303	3.8	1000-1004	234	3.4			
64	1004-1008	214	227	1006-1007	150-300	3.9		1000		1004-1008	234	3.7			
65	1008-1013	202	245	1010-1011	200-300	3.8		1000		1008-1013	234	3.4			
66	1013-1018	479	340	1015	300-400	3.4		1000		1013-1018	224	3.5			
67	1019-1023	504	320	1019-1023	300	4.3		1000		1019-1023	173	3.8			
68	1036-1039	204	229	1036-1037	150-300	5.3	1037-1038	150-300	4.9	1031-1039	173	3.9	1036	97-306	2.3
69	1040-1044	233	239	1040-1041	200-300	5.5	1041	200-300	5.2	1040-1044	173	3.5			
70	1100-1108	219	237	1105	200-300	4.5	1100-1108	200-300	4.5	1100-1108	173	3.8			
71	1116-1120	217	225	1116-1120	150-300	5.4	1118-1119	150-300	4.1	1116-1120	173	4.0			
72	1121-1126	221	240	1120-1126	200-300	4.4	1122-1126	200-300	3.4	1121-1126	173	1.2			
73	1126-1132	417	305	1129	300	3.6	1127	400	3.1	1126-1132	155	3.2	1131	202-306	2.3
74	1132-1138	477	328	1129	300-400	4.2				1132-1138	112	3.0			
75	1138-1143	540	345	1129	300-400	4.2				1138-1143	112	3.5			
76	1150-1155	247	255							1150-1155	112	2.5			
77	1156-1201	310	277							1156-1201	112	1.7			
78	1211-1216	426	343	1217	300-400	3.8	1217-1218	300-400	2.8	1211-1216	112	2.8			
79	1216-1221	500	344	1217-1221	300-400	4.4	1217-1222	300-400	3.5	1216-1221	112	3.5			
80	1221-1227	539	325	1221-1225	300-400	4.6	1221-1225	300-400	4.0	1221-1227	112	2.7			
81	1308-1310	259	253	1310-1311	200-300	5.4	1311	200	3.7	1308-1310	81 ↵	3.6			
82	1310-1313	256	255	1310-1311	200-300	5.4	1311	200	3.7	1311-1313	81 ↵	2.3			
83	1314-1318	319	288	1315	300	4.0	1318	200	3.5	1314-1318	81 ↵	2.1			
84	1319-1323	267	239	1319-1323	200-300	5.0	1323	300	6.6	1319-1323	81 ↵	2.4			
85	1328-1331	265	250	1330-1331	200-300	4.2	1330	200	5.4	1328-1331	81 ↵	3.8			
86	1331-1334	259	245	1331-1334	200-300	4.6				1331-1334	81 ↵	3.4			

(continued)

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TABLE 1 (continued)

TRAV-ERSE NO.	TIME (MDT)	STACK DIST. (M)	PLUME HEIGHT (M)	LDV			LDV'			TETHERSONDE			PIBAL		
				TIME (MDT)	HEIGHT (M)	SPEED (M/S)	TIME (MDT)	HEIGHT (M)	SPEED (M/S)	TIME (MDT)	HEIGHT (M)	SPEED (M/S)	TIME (MDT)	HEIGHT (M)	SPEED (M/S)
87	1345-1350	293	265	1352-1353	200-300	5.9				1345-1350	81	3.2			
88	1351-1354	304	253	1352-1353	200-300	5.9				1351-1354	81	2.9	1401	97-306	2.4
89	2032-2035	248	437	2034-2035	400-500	2.0				2033-2035	142	1.7			
90	2035-2038	210	430	2038	400-500	1.9				2035-2038	142	1.8			
91	2041-2047	50	240	2041-2046	200-300	1.9				2041-2047	173	1.8			
92	2048-2056	52	243	2049-2054	200-300	1.8				2048-2056	173	1.8			
93	2056-2103	36	208	2057-2101	150-200	1.9				2056-2103	173	1.8			
	6 AUG 76														
94	0918-0923	201	250	0919-0923	200-300	3.9	0919-0923	200	3.4	0918-0923	295	3.6			
95	0931-0934	207	213	0934	150-200	5.5	0930-0934	150-200	4.2	0931-0934	264	3.4			
96	0934-0937	221	232	0935	200-300	5.2	0934-0935	200-300	3.6	0934-0937	264	4.1			
97	0937-0941	208	223	0938-0939	150-300	4.2	0938	150-300	4.5	0937-0941	264	3.9			
98	0941-0944	206	218	0942	150-200	5.1	0941-0942	150-200	4.1	0941-0944	264	4.0			
99	0944-0947	214	208	0942-0949	150-200	6.1	0945-0946	150-200	4.3	0944-0947	264	4.5			
100	0947-0951	211	207	0949	150-200	7.2	0949	150-200	4.2	0947-0951	264	5.0	0951	97-202	5.7
101	0951-0954	208	203	0953	150-200	7.0	0953	150-200	5.8	0951-0954	264	5.5			
102	0957-1001	496	273	0957-1001	200-300	6.0	0957-1001	200-300	5.6	0957-1000	264	5.7			
103	1005-1008	1061	374	1001	200-300	6.1	1005	300-400	5.8						
104	1033-1038	206	205	1035	150-200	6.0	1034-1035	150-200	5.1	1005-1038	173	5.9			
105	1039-1043	532	267	1039-1043	200-300	7.0	1039-1043	200-300	6.0	1039-1043	173	5.8			
106	1043-1045	205	198	1042	150-200	7.3	1042-1046	150-200	6.0	1043-1045	173	5.8			
107	1046-1050	407	268	1049-1050	200-300	5.5	1046-1050	200-300	5.2	1046-1050	173	5.5			
108	1053-1056	209	211	1053	150-200	5.4	1053-1054	150-200	5.1	1053-1056	173	5.0			
109	1057-1102	527	279	1057-1102	200-300	6.1	1058-1102	200-300	5.5	1057-1102	173	5.5			
110	1103-1105	207	213	1105	150-200	5.8	1105	150-200	4.6	1103-1105	173	4.5			
111	1105-1110	548	303	1106-1110	300	6.3	1105-1110	200-300	5.8	1105-1110	173	4.9			
112	1112-1115	221	220	1113	150-200	5.6	1113	150-200	5.7	1112-1115	173	5.1			
113	1115-1120	505	291	1118	300	6.4	1117-1121	300	6.3	1115-1120	173	5.3			
114	1120-1126	437	263	1121-1126	200-300	5.5	1121-1124	200-300	5.9	1120-1126	173	5.4			
115	1126-1129	230	212	1127	150-200	5.7	1128	150-200	6.1	1126-1129	173	5.2			
116	1130-1135	549	286	1132	300	6.1	1132-1133	200-300	5.1	1130-1135	173	5.1			
117	1135-1139	271	226	1135-1136	150-300	5.5	1135-1139	150-200	6.3	1135-1139	173	5.2			
118	1143-1147	237	212	1143-1147	250-300	6.2	1143-1147	150-200	5.7	1145-1147	173	5.4			
119	1147-1151	234	212	1146-1150	150-200	6.4	1147-1151	150-200	7.0	1147	173	5.6			
120	1151-1156	288	226	1151	150-200	7.0	1151-1155	150-300	6.8				1205	97-306	7.2

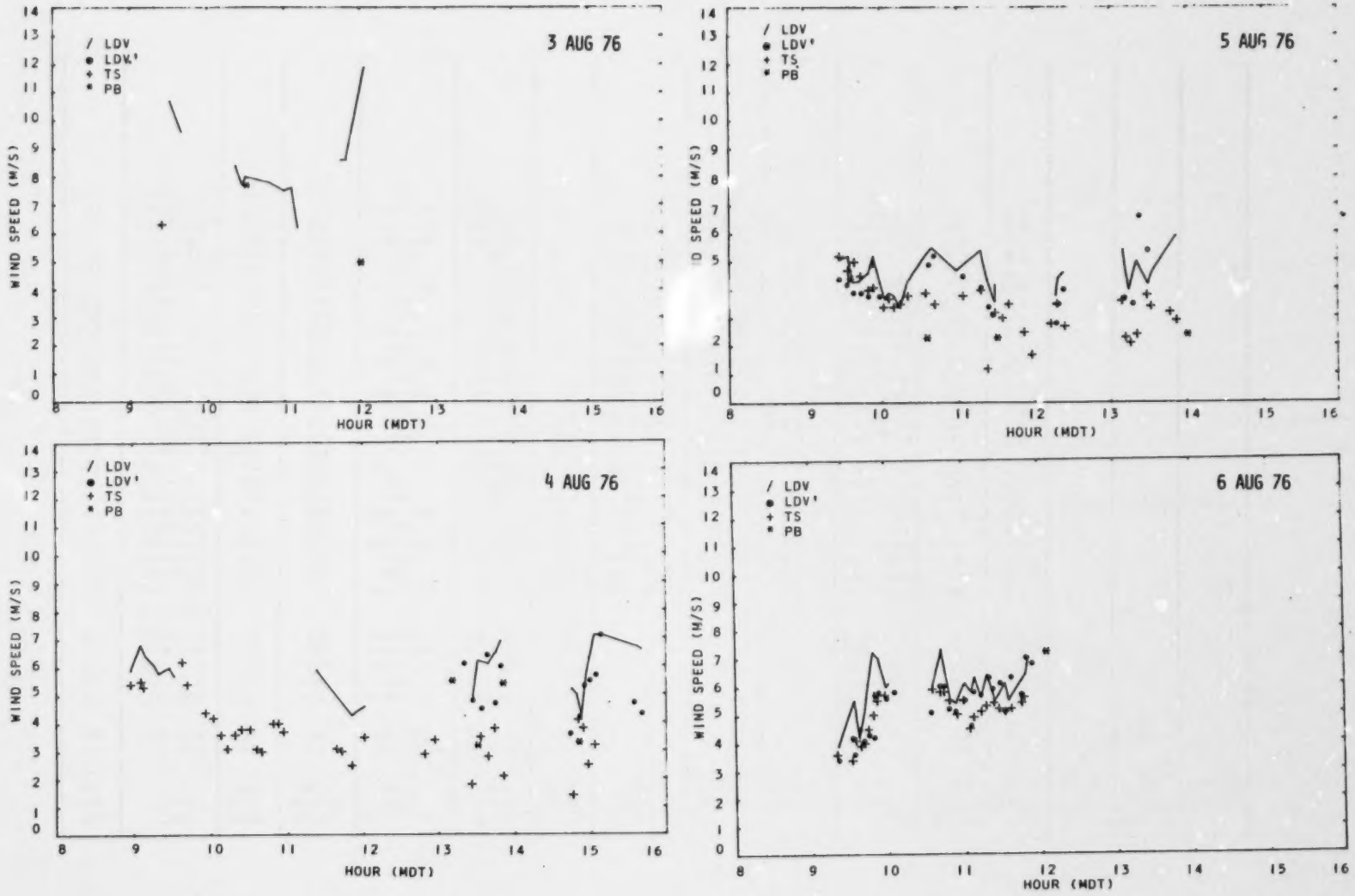

Figure 4. Wind Speed by Day

millivolts different from the other side, the traverse was considered to be invalid due to an incomplete traverse of the plume or another sampling problem. This background value was then subtracted from each 20-meter average for the traverse. When the resulting values were negative (due to instrument noise), the result was considered zero.

The next step was to multiply the adjusted millivolt readings by the calibration factor. This factor was determined from a calibration curve that was made up of data from all calibrations made during the test period. The calibration factor is time-dependent because the COSPEC's response varies markedly with the sun angle. This variation was considered to be consistent during the week of field work; therefore, the same time-dependent calibration curve was used each day.

Because of the non-linear response above 600 ppmM of the particular COSPEC used in this study*, an additional step was required to prepare the COSPEC data for flux calculations. Extensive tests were made in 1975 of the linearity of the two COSPECs used in this study. From the information gathered in these tests a curve was constructed to estimate readings for values about 600 ppmM SO_2. Values from the curve were then used in a polynominal regression to determine a conversion formula to obtain true ppmM values for those readings over 600 pppM. When this was completed, the COSPEC results were ready to be used for flux calculations.

GFC

The Gas Filter Correlation instrument data had not been previously processed because the sensitivity (ppmM SO_2/mv) was not available.[1] Using a calibration curve provided by the Project Officer[6] for 5 August 1976 (judged the most suitable data to be processed), the sensitivities were found to be:

- 5.88 ppmM SO_2/mv (day)
- 6.58 ppmM SO_2/mv (night)

Following the same procedure used with the COSPEC the zero reference level was determined for the millivolt readings for each of 33 GFC plume profiles. This was more difficult for the GFC because the profiles were less distinct than the typical COSPEC profile. In addition there was greater drift from one edge of the plume to the other, necessitating the subtraction

---

*Note added in review: It is now possible to execute special fine tuning to eliminate this high concentration nonlinearity for COSPEC II and III.

of sloped zero-reference lines. (No non-linearity correction was required.) The next step was to apply the sensitivities to yield the ppmM SO_2 optical depth values for processing into mass emission rates.

SO_2 Mass Flux

The mass emission rates were calculated from the three remote sensor SO_2 optical depths, the four sets of wind velocities, and the geography (X-Y coordinates) provided by the MAP System. The procedure, described in detail elsewhere[2], is summarized below.

The SO_2 Mass Flux is calculated by the formula:

$$SO_2 \text{ FLUX} = \Sigma \text{ (summation of individual segments of traverse)} (C \times \sin \alpha \times l \times \upsilon \times F)$$

where C = COSPEC optical depth reading in ppmM (average value during one segment)

l = length of road segment

α = angle between road segment and wind direction

υ = wind speed

F = conversion factor used to obtain MT/D SO_2.

As the COSPEC passes under the plume, it measures the total burden of SO_2 which is output by the MAP System as an average value each 20 meters along the road. To obtain the flux of gas across any segment the optical depth in ppmM is multiplied by the length of the segment to obtain the total gas above the segment. This value is multiplied by the sine of the angle between the wind direction and the road segment to account for the fact that the road may not be perpendicular to the flow of the gas. Finally, multiplying by the wind speed and a conversion factor to convert to metric tons per day (MT/D) gives the final result. The sum of these calculations over one traverse gives a value for total mass flux. The sine α term equals unity if the X-Y values are projected onto a line perpendicular to the wind direction. This step effectively shortens the segment length in proportion to the line of the wind/road angle and allows for calculation of the center of mass and movements about the center of mass.

Because the direction of the wind can vary dramatically during a short time, the wind direction was derived from the center of mass of each traverse rather than as measured by one of the wind sensors. This value gives the best estimate of true plume direction but does not account for possible wind shear.[7]

Flux Calculations

Once the necessary calibration and nonlinearity factors had been applied to the data and the appropriate wind speed had been chosen, the data were ready for the actual flux computer calculations. The following outlines the methodology of the flux calculation program. Once the data to be used were loaded into the computer memory, the center of mass of the COSPEC data was calculated.

Because the gas flowing across the surface perpendicular to the wind direction is of interest, the X-Y points of the traverse are projected onto the line perpendicular to the stack-traverse midpoint segment, using the assumption that the wind is blowing parallel to the stack/midpoint vector. An example of the computer printout for the flux calculation is shown in Figure 5.

EPA SPECTROMETER EVALUATION: SO2 MASS FLUX AND STATISTICS CALCULATIONS

DATE: 4 AUGUST 76 TRAVERSE # 16

TIME: 0804- 0836 MDT WIND SPEED: 6.8 MPS

INSTRUMENT: 1

SEGMENT #	W.R ANGLE	SEG LENGTH	SO2 PPMM	AREA PPMM2	FLUX MT/DAY	SUM MT/DAY	
120	103	37	3	113	0.2	0.2	0.13
121	102	20	1	132	0.0	0.2	0.03
122	103	19	3	191	0.1	0.3	0.09
123	103	21	3	256	0.1	0.4	0.10
124	103	20	0	256	0.0	0.4	0.00
125	103	19	0	256	0.0	0.4	0.00
126	103	21	12	497	0.4	0.8	0.38
127	103	20	41	1314	1.3	2.1	1.28
128	103	19	247	5977	7.3	9.3	7.20
129	103	20	361	13126	11.2	20.5	11.16
130	101	20	589	24849	18.3	38.8	18.30
131	101	21	133	27428	4.0	42.8	4.00
132	103	19	6	27549	0.2	43.0	0.19
133	101	20	9	27714	0.3	43.3	0.27
134	101	21	9	27897	0.3	43.6	0.28
135	101	20	1	27919	0.0	43.6	0.03
136	103	20	1	27979	0.1	43.7	0.10
137	103	19	0	27979	0.0	43.7	0.00
138	101	21	7	28105	0.2	43.9	0.24
139	100	16	0	28105	0.0	43.9	0.00

S.O. MASS FLUX: 43.90887808 METRIC TONS DAY
1 KILOGRAMS HOUR

CENTER OF MASS COORDINATE: 721565.0788 -075692.648

PT. NEAREST C OF M: 129 721565.3810 4075694.19

1ST SEGMENT: 112.5440295
ANGLE TO PT NEAREST C OF M: -11.68719469
ANGLE TO INITIAL PT: -11.68719492

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Figure 5. Typical flux calculation printout

Plume Profiles

At the time each flux calculation was made, an individual plume profile was plotted. Figure 6 shows eight representative plume profiles. The traverse route is shown as a straight or curved line, and the projection line is drawn normal to the plume axis (not shown, but the stack is indicated by a dot). The plume profile is plotted "away" from the stack, parallel to the wind flow. These plume profiles were useful as an editing tool and played a major part in the analysis of the flux results.

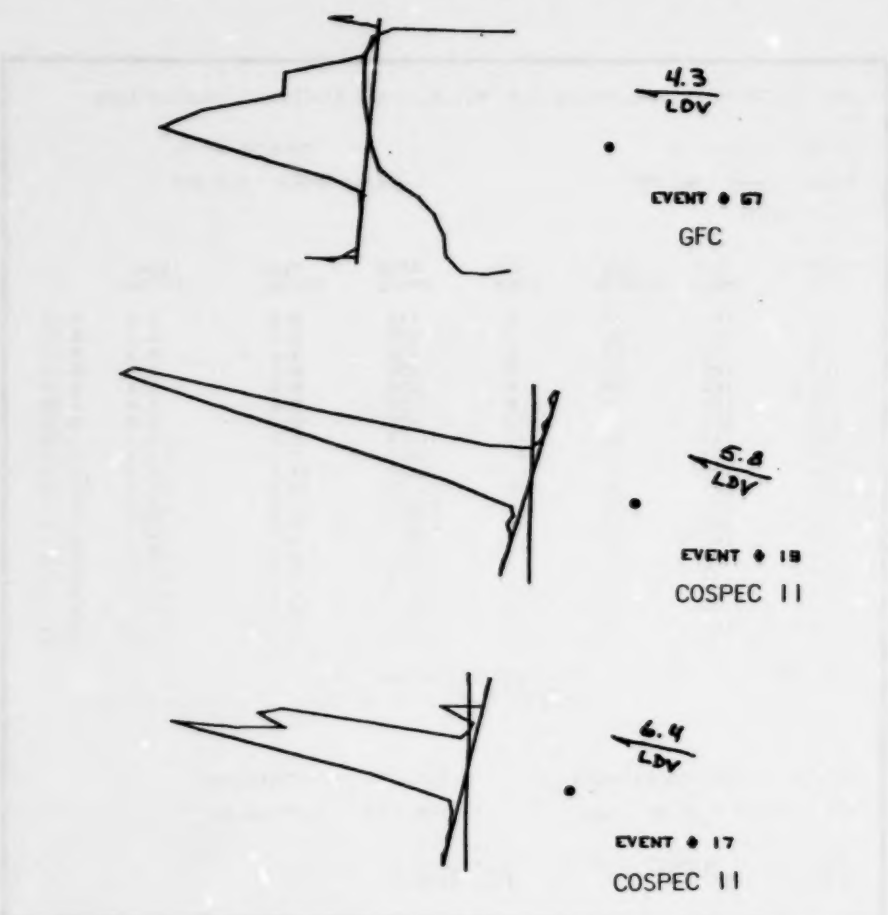

Figure 6. Typical plume profiles
(continued)

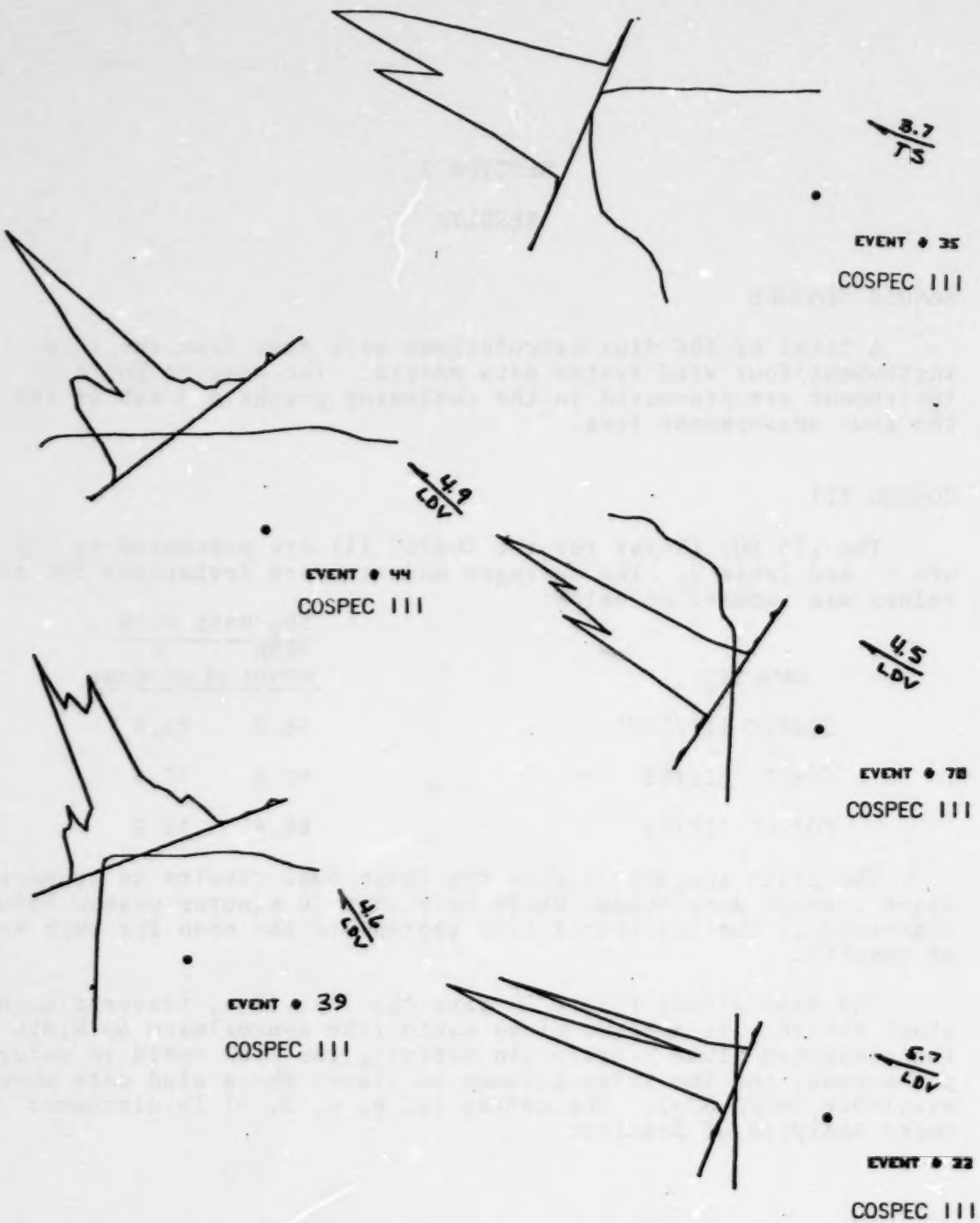

Figure 6. (continued)

SECTION 5

RESULTS

REMOTE SENSORS

A total of 308 flux calculations were made from the three instrument/four wind system data matrix. The results for each instrument are presented in the following graphs and tables for the four measurement days.

COSPEC III

The 176 SO_2 fluxes for the COSPEC III are presented in Figure 7 and Table 2. The averages and standard deviations for all values are summarized below:

DATA SETS	SO_2 MASS FLUX MEAN (MT/D)	SO_2 MASS FLUX σ (% of MEAN)
COSPEC III/LDV'	78.9	40.9
COSPEC III/TS	64.9	37.0
COSPEC III/PB	68.4	38.9

The plots (Figure 7) show the individual results as connected lines (except dots appear where more than 30 minutes passed between traverses). The horizontal line represents the mean for each set of results.

The tabulations (Table 2) give the day, time, traverse number, stack distance in meters, plume width (the approximate 6σ width of the projected plume profile (in meters), the wind speed in meters per second, and the three columns of fluxes where wind data were available (MT/D SO_2). The coding (a, b, c, d, e) is discussed under Analysis of Results.

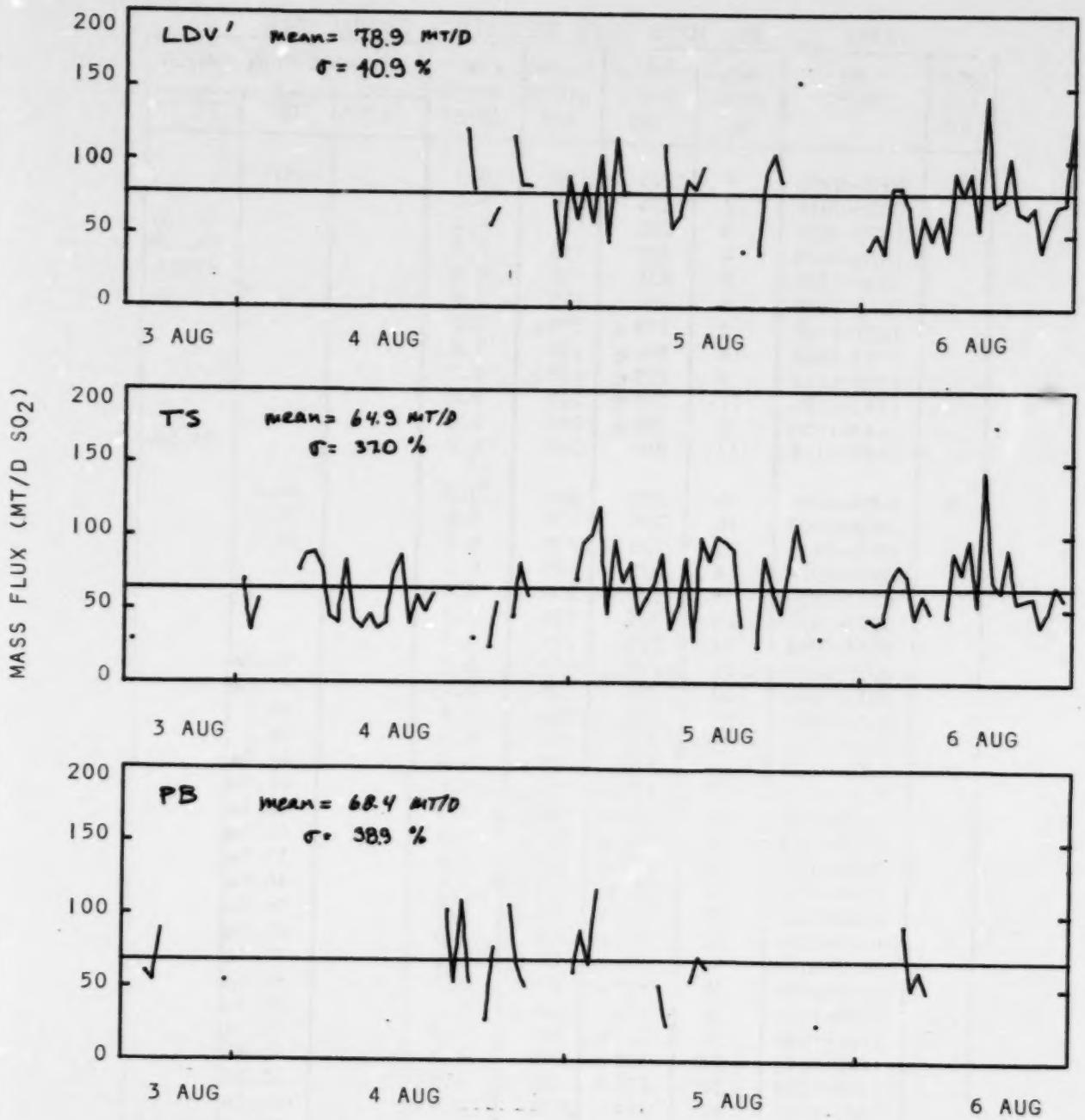

Figure 7. COSPEC III SO_2 Mass Flux Results

TABLE 2. SO_2 MASS FLUX RESULTS - COSPEC III

DATE AUG 1976	TIME (MDT)	TRAV-ERSE NO.	STACK DIST. (M)	PLUME WIDTH (M)	WIND SPEED (M/S)	SO_2 MASS FLUX (MT/D)		
						LDV[1]	TS	PB
3	0929-0933	1	225	150	10.7		29.0	
	0936-0941	2	225	150	9.6			
	1020-1024	3	200	175	8.4			60.1b
	1026-1029	4	225	150	7.7			54.1b
	1032-1035	5	225	175	8.0			89.3b
	1047-1049	6	250	125	7.8			
	1057-1102	7	275e	300c	7.5			
	1103-1108	8	300e	150	7.6			
	1109-1112	9	275e	175c	6.2			
	1143-1146	11	275e	225	8.5			
	1147-1150	12	300e	250	8.6			
	1157-1159	13	250	250	11.9			54.5b
4	0856-0901	15	200	200	5.9		69.4	
	0904-0908	16	225	175	6.8		35.5	
	0908-0913	17	225	175	6.4		56.5	
	0913-0916	18	225	175	6.1			
	0917-0920	19	225	200	5.8			
	0925-0929	20	225	150	6.0			
	0931-0934	21	225	175	5.7			
	0935-0938	22	225	175	5.7		76.7a	
	0938-0942	23	225	175	5.7		87.4a	
	0954-0959	24	250	225	4.4		89.2	
	1000-1003	25	225	175	4.2		78.6	
	1007-1010	26	575	325c	3.6		44.4a	
	1011-1015	27	375e	350c	3.1		41.0a	
	1016-1022	28	550e	350c	3.6		82.7a	
	1022-1027	29	525e	350c	3.8		43.0a	
	1029-1034	30	550e	350c	3.8		37.3a	
	1034-1038	31	575e	375c	3.1		46.0a	
	1038-1042	32	550e	300c	3.0		36.8a	
	1047-1051	33	550e	325	4.0		40.7a	
	1052-1055	34	550e	350c	4.0		75.4a	
	1055-1059	35	575e	325c	3.7		86.7a	
	1138-1141	36	275	225c	5.9		40.5a	
	1141-1146	37	225e	300	5.9		58.9a	
	1149-1154	38	300e	275	4.3		48.8a	
	1158-1204	39	275e	400	4.6		60.3a	
	1247-1251	40	250	d450	2.9		108.2a	
	1257-1304	41	275	325	3.4		63.6a	102.9b
	1305-1310	42	250	150	5.5			53.9b
	1316-1321	43	250	275	4.9	121.0		109.1b
	1321-1328	44	300	400	4.9	80.7a	30.3a	53.8b

(continued)

TABLE 2. (continued)

DATE AUG 1976	TIME (MDT)	TRAV-ERSE NO.	STACK DIST. (M)	PLUME WIDTH (M)	WIND SPEED (M/S)	SO_2 MASS FLUX (MT/D)		
						LDV[1]	TS	PB
4	1330-1336	45	250	450	6.2	77.2	60.0 a	54.9
	1338-1341	46	275	200	6.1	56.3	24.6 a	28.2 b
	1342-1347	47	325	300	6.5	67.7	54.7 a	77.8 b
	1444-1448	49	275	275	5.2	116.0	45.0 a	106.0 b
	1449-1452	50	275	225	5.0	83.3	81.3 a	65.5
	1452-1456	51	300	300	4.3	82.5	59.1 a	51.3
	1456-1501	52	275	425	5.8	137.1	62.3 a	82.3 b
	1506-1512	54	250 e	250	7.1	72.5		
	1533-1538	55	475	250 c	6.7	35.2		
	1538-1543	56	475	400 c	6.6	89.6		
5	0924-0930	57	225	200	5.1	60.9	70.2	60.9 b
	0932-0937	58	225	200	5.2	85.0	95.2	89.1
	0937-0941	59	225	200	4.3	58.7	101.2	66.2
	0941-0948	60	225	200	4.3	103.8	119.7	117.1 b
	0948-0952	61	225	175	4.6	44.8	47.1	
	0952-0957	62	225	200	5.2	116.0	97.1	
	1000-1004	63	225	200	3.7	77.1	69.0	
	1004-1008	64	225	200	3.9		81.9	
	1008-1013	65	225	175	3.8		47.2	
	1013-1018	66	575 e	350 c	3.4		57.7 a	
	1019-1023	67	550 e	300	4.3		68.1 a	
	1036-1039	68	225	275	5.3	110.5	87.9	51.8
	1040-1044	69	250	275	5.5	54.7	36.8	24.2 b
	1100-1108	70	250	200	4.5	62.7	52.9	
	1116-1120	71	225	225	5.4	87.0	84.9	
	1121-1126	72	225 e	275	4.4	81.3	28.7	55.0 b
	1126-1132	73	500 e	450 c	3.6	95.7 a	98.8 a	71.0
	1132-1138	74	475 e	450 c	4.2		83.6 a	64.1
	1138-1143	75	575 e	475	4.2		99.9 a	
	1150-1155	76	450 e	700 c	2.5		96.1 a	
	1156-1201	77	300 e	750	1.7		91.5 a	
	1211-1216	78	575 e	450 c	3.8	39.0 b	39.0 a	
	1221-1227	80	575 e	475 c	4.6	36.8	24.8 a	
	1308-1310	81	250	425	5.4	92.0 b	89.5 a	
	1310-1313	82	250	375	5.4	104.9	65.2 a	
	1314-1318	83	300	425	4.0	86.7 a	47.9 a	
	1319-1323	84	275	650	5.0	208.1	75.7 a	
	1328-1331	85	275	500	4.2	154.3	108.6 a	
	1331-1334	86	275	375	4.6		84.2 a	
	1351-1354	88	325	450	5.9		30.6 a	25.3 b
6	0918-0923	94	200	175	3.9	40.7	43.1	

(continued)

TABLE 2. (continued)

DATE AUG 1976	TIME (MDT)	TRAV-ERSE NO.	STACK DIST. (M)	PLUME WIDTH (M)	WIND SPEED (M/S)	SO_2 MASS FLUX (MT/D)		
						LDV[1]	TS	PB
6	0931-0934	95	225	200	5.5	50.1	40.4	
	0934-0937	96	250	150	5.2	37.9	43.2	
	0937-0941	97	225	200	4.2	82.2	71.2	
	0941-0944	98	225	250	5.1	82.2	80.2	
	0944-0947	99	225	175	6.1	69.7	72.9	92.4b
	0947-0951	100	225	150	7.2	36.8	43.8	49.9b
	0951-0954	101	225	150	7.0	62.6	59.4	61.6
	0957-1001	102	550	275	6.0	47.0	47.9	47.9b
	1005-1008	103	1125	225	6.1	62.6		
	1033-1038	104	225	150	6.0	39.4	45.6	
	1039-1043	105	550e	275	7.0	92.0	89.0	
	1043-1045	106	225	250	7.3	77.5	74.9	
	1046-1050	107	425	275	5.5	91.9	97.2a	
	1053-1056	108	225	175	5.4	53.9	52.8	
	1057-1102	109	550	300	6.1	144.2	144.2a	
	1103-1105	110	250	200	5.8	70.0	68.5	
	1105-1110	111	575e	250	6.3	73.7	62.3a	
	1112-1115	112	225	200	5.6	102.3	91.5	
	1115-1120	113	550e	275c	6.4	65.6	55.2a	
	1120-1126	114	550e	300c	5.5	62.4	57.1a	
	1126-1129	115	250	125	5.7	68.8	58.7	
	1130-1135	116	575e	275c	6.1	39.2	39.2a	
	1135-1139	117	250e	175	5.5	58.8	48.5	
	1143-1147	118	275	200	6.2	70.0	66.4	
	1147-1151	119	250	150	6.4	71.6	57.3	
	1151-1156	120	275e	150	7.0	124.7		132.0b

COSPEC II

The 54 SO_2 fluxes for the COSPEC II are presented in Figure 8 and Table 3. The averages and standard deviations for all values are summarized below:

DATA SETS	SO_2 MASS FLUX MEAN (MT/D)	SO_2 MASS FLUX σ (% of MEAN)
COSPEC II/LDV'	63.4	28.2
COSPEC II/TS	50.6	37.3
COSPEC II/PB	51.7	32.0

The plots and tabulations are identical to the preceding COSPEC III presentations.

GFC

The 57 SO_2 fluxes for the GFC are presented in Table 4. The averaged and standard deviations for all values are summarized below:

DATA SETS	SO_2 MASS FLUX MEAN (MT/D)	SO_2 MASS FLUX σ (% of MEAN)
GFC/LDV'	204.8	20.2
GFC/TS	139.4*	50.3
GFC/PB	109.8	50.4

*Includes four night traverses

The GFC flux calculations were limited to one day only, 5 August 1976, because of an accumlulation of dust on the instrument mirror and other problems that occurred in the field.

The tabulation is the same as the preceding COSPEC III presentation. No plot of the GFC results is offered as they are clearly divergent by a factor of two or more from the COSPEC/ Method 6 values.

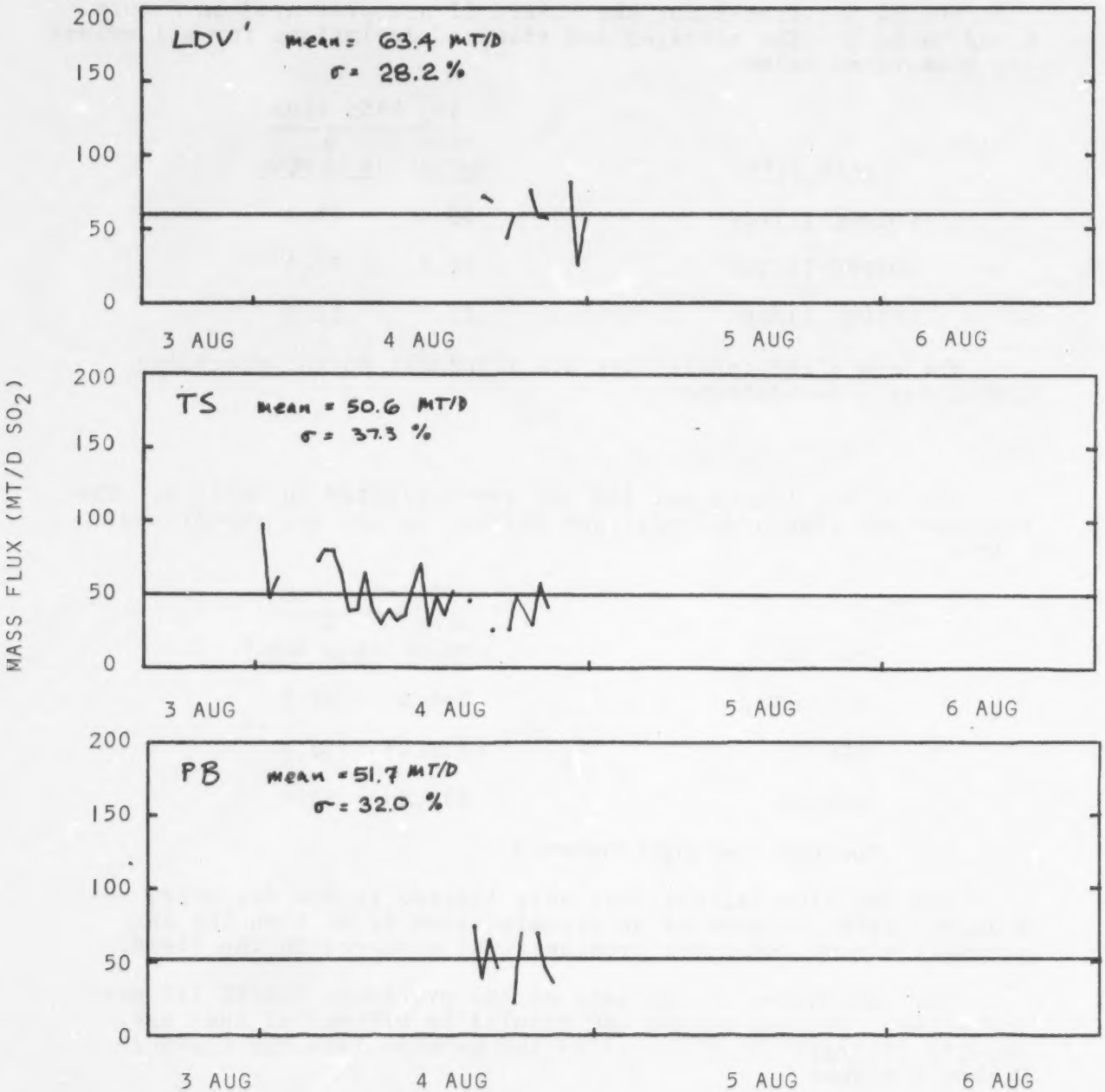

Figure 8. COSPEC II SO_2 Mass Flux Results

TABLE 3. SO_2 MASS FLUX RESULTS - COSPEC II

DATE AUG 1976	TIME (MDT)	TRAV-ERSE NO.	STACK DIST. (M)	PLUME WIDTH (M)	WIND SPEED (M/S)	SO_2 MASS FLUX (MT/D)		
						LDV'	TS	PB
4	0856-0901	15	225	200	5.9		97.2	
	0904-0908	16	225	200	6.8		47.3	
	0908-0913	17	225	225	6.4		61.5	
	0913-0916	18	225	175	6.1			
	0917-0920	19	225	200	5.8			
	0925-0929	20	225	125	6.0			
	0931-0934	21	225	125	5.7			
	0935-0938	22	225	150	5.7		72.7a	
	0938-0942	23	225	175	5.7		80.1a	
	0954-0959	24	225	200	4.4		80.2	
	1000-1003	25	225	175	4.2		65.0	
	1007-1010	26	575e	275c	3.6		39.0a	
	1011-1015	27	575e	300c	3.1		40.1a	
	1016-1022	28	550e	300c	3.6		64.1a	
	1022-1027	29	475e	350c	3.8		39.4a	
	1029-1034	30	525e	300c	3.8		30.1a	
	1034-1038	31	575e	275c	3.1		39.6a	
	1038-1042	32	550e	300c	3.0		32.3a	
	1047-1051	33	550	325	4.0		35.8a	
	1052-1055	34	550e	325c	4.0		55.0a	
	1055-1059	35	575	300c	3.7		70.4a	
	1138-1141	36	250	200c	5.9		28.6a	
	1141-1146	37	250e	275	5.9		48.5a	
	1149-1154	38	300e	175	4.3		36.3a	
	1158-1204	39	300e	375	4.6		52.0a	
	1247-1251	40	250	450d	2.9		87.4a	
	1257-1304	41	250	275	3.4		45.9a	74.2b
	1305-1310	42	275	150c	5.5			38.7b
	1316-1321	43	250	200	4.9	72.1		65.0b
	1321-1328	44	250	400	4.9	69.2a	25.9a	46.1b
	1330-1336	45	250	450d	6.2	63.0	49.0a	44.8
	1338-1341	46	275	175	6.1	44.6	26.5a	22.3b
	1342-1347	47	300	275	6.5	60.2	48.7a	69.2b
	1444-1448	49	275	275	5.2	75.6	29.4a	69.3b
	1449-1452	50	300	250	4.3	58.5	57.1a	45.9
	1452-1456	51	325	250	4.3	57.2	41.0a	35.6
	1456-1501	52	275	425d	5.8	95.8	43.5a	57.5b
	1506-1512	54	250e	225	7.1	81.4		
	1533-1538	55	450	175c	6.7	25.5		
	1538-1543	56	500	400c	6.6	57.2		

TABLE 4. SO_2 MASS FLUX RESULTS - GFC

DATE AUG 1976	TIME (MDT)	TRAV-ERSE NO.	STACK DIST. (M)	PLUME WIDTH (M)	WIND SPEED (M/S)	SO_2 MASS FLUX (MT/D)		
						LDV'	TS	PB
5	0932-0937	58	225	250	5.2	140.3	157.0	147.0
	0937-0941	59	200	250	4.3	128.3	164.5	144.8
	0941-0948	60	225	275	4.3	176.8	204.0	199.5b
	0948-0952	61	200	350	4.6	167.5	176.3	
	0952-0957	62	225	250	5.2	222.9	186.6	
	1000-1004	63	200	275	3.7	169.0	151.6	
	1008-1013	65	200	200	3.8		77.5	
	1013-1018	66	500	250	3.4		39.7	
	1019-1023	67	500c	350	4.3		61.0	
	1036-1039	68	200	375	5.3	28.5	22.7	13.7
	1100-1108	70	250	275	4.5	223.0	118.3	
	1116-1120	71	200	350	5.4	250.6	244.4	
	1121-1126	72	200c	375	4.4	120.6	42.6	81.5b
	1126-1132	73	475c	425c	3.6	120.9	124.8a	89.7
	1132-1138	74	475c	475c	4.2		141.5a	108.5
	1138-1143	75	525c	575c	4.2		234.0a	
	1150-1155	76	350c	675	2.5		267.5a	
	1156-1201	77	375c	575	1.7		212.6a	
	1211-1216	78	500c	500	3.8	372.2b	372.2a	
	1221-1227	80	500c	475	4.6	207.1	139.8a	
	1308-1310	81	250	400	5.4	94.8b	92.2a	
	1310-1313	82	250	325	5.4	181.8	113.0a	
	1314-1318	83	375	300c	4.0	73.8a	44.3a	
	1319-1323	84	275	525	5.0	406.4	147.8a	
	1328-1331	85	300	700	4.2	601.6	423.3a	
	1331-1334	86	275	400	4.6		99.6a	
	1351-1354	88	300	500	5.9		124.7a	93.6
	2032-2035	89	250c	275	2.0		85.1a	
	2035-2038	90	200	450	1.9		25.7a	
	2052-2055	92	50c	350	1.8		10.4	
	2059-2102	93	50	375	1.8		15.5	

REFERENCE METHOD 6

The 25 stack sampling results are presented in Figure 9 and Table 5. The plot is to the same scale as the remote sensor for ease of comparison of the two sets of data. The overall average and standard deviations are:

DATA SETS	SO_2 MASS FLUX MEAN (MT/D)	SO_2 MASS FLUX σ (% of MEAN)
Method 6 / Method 2	67.4	8.7

It must be noted that no corrections for moisture have been applied to these reference method data. Any further analysis that compares the Method 6 results with the COSPEC results should first make the necessary correction before making the comparisons.

The "annulus" results quantify the SO_2 flux between the inner and outer stacks; less than 1% of the SO_2 was found in the annulus.

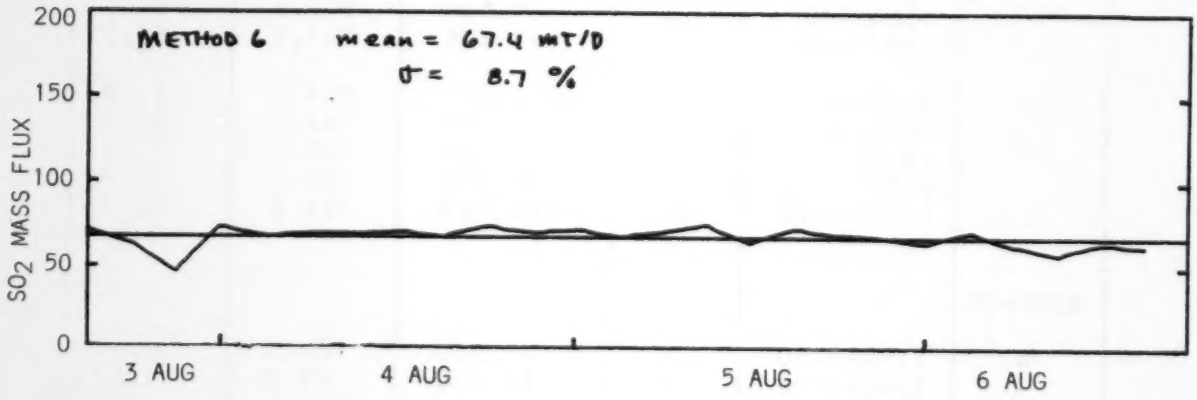

Figure 9. Reference Method 6 Mass Flux

TABLE 5. STACK SAMPLING RESULTS - EPA METHOD 6

DATE AUG 1976	TIME (MDT)	RUN NO.	STACK GAS FLOW RATE (ScFm)	SULFUR DIOXIDE CONC. (ppmv)	SULFUR DIOXIDE FLUX (MT/D)
3	1020-1040	1	782,000	830.9	70.8
	1153-1113	2	782,000	744.3	63.4
	1125-1145	3	782,000	551.8	47.0
	1320-1340	4	782,000	856.0	72.9
4	0851-0911	5	758,000	822.9	67.9
	0923-0943	6	758,000	840.2	69.4
	1005-1025	7	758,000	835.3	69.0
	1041-1101	8	765,000	846.5	70.5
	1143-1203	9	765,000	812.8	67.7
	1319-1339	10	765,000	885.5	73.8
	1358-1418	11	771,000	837.7	70.3
	1500-1520	12	771,000	856.3	71.9
5	0912-0932	13	761,000	820.9	68.0
	0942-1002	14	766,000	847.6	70.7
	1039-1059	15	766,000	899.3	75.0
	1105-1125	16	766,000	776.4	64.8
	1131-1151	17	770,000	866.2	72.6
	1210-1230	18	770,000	825.2	69.2
	1304-1324	19	769,000	807.9	67.7
	1343-1403	20	767,000	773.1	64.5
6	0915-0935	21	752,000	864.9	70.8
	0945-1005	22	752,000	769.0	63.0
	1015-1035	23	756,000	702.7	57.9
	1056-1116	24	756,000	780.7	64.3
	1129-1149	25	756,000	758.2	62.4
ANNULUS					
4	1130-1150	1	43,500	140.6	0.67
	1240-1300	2	57,400	53.7	0.34
5	1008-1028	3	52,300	94.5	0.54
	1328-1348	4	52,700	139.0	0.80
6	1106-1126	5	44,500	34.2	0.17

ANALYSIS of RESULTS

Measurement Errors

The initial analysis of the results was an attempt to identify known errors in the collection and processing of the remote sensor and wind data that could contribute to erroneous calculated SO_2 flux values. Five potential errors were identified:

ERROR CODE	DESCRIPTION
a	Altitude of the selected wind speed was outside the assumed plume vertical dispersion (±75 meters from plume axis).
b	Time of the selected wind velocity was outside the time window for the traverse.
c	The Wind/Road angle was greater than ±50°. (Traverse road exactly normal to the plume axis is 0°.)
d	Double plume measurement based on criteria of one or more instruments returning to a 0-10% SO_2 optical depth reading, creating distinct double peaks.
e	Traverse route was on a corner, thus increasing the chances of non-normal plume crossing and double plume measurement.

The wind velocity errors (*a*,*b*) were coded into the wind summary (Table 1) and carried through to the flux summaries (Tables 2, 3, 4). The plume profile and traverse road geometry errors (*c*,*d*,*e*) were coded into the flux results (Tables 2, 3, 4).

Figure 10 presents four examples of Error *c* (Wind/Road angle > ±50°). These happen to occur mostly at a corner, used for traversing when the wind was from the southeast. (Note the wind arrows labelled with wind speed in meters per second and letters identifying the source of the data.)

Figure 11 shows four examples of Error *e*, corner measurements. (Though many traverses had both *c* and *e* Errors, not all did.) Two different corners are shown. (Note different stack distance.) Error *d*, double plumes, is described below.

Plume Bifurcation

Another phenomenon that must be considered in the processing of remote sensor data is the bifurcated plume, the division of the plume profile into two (or more) distinct peaks with a differing degree of separation.[7] Figure 12 shows four examples of bifurcated plumes, and Figure 13 shows two truly double plume profiles. This was also noted in 1975 work at the same power plant.[2]

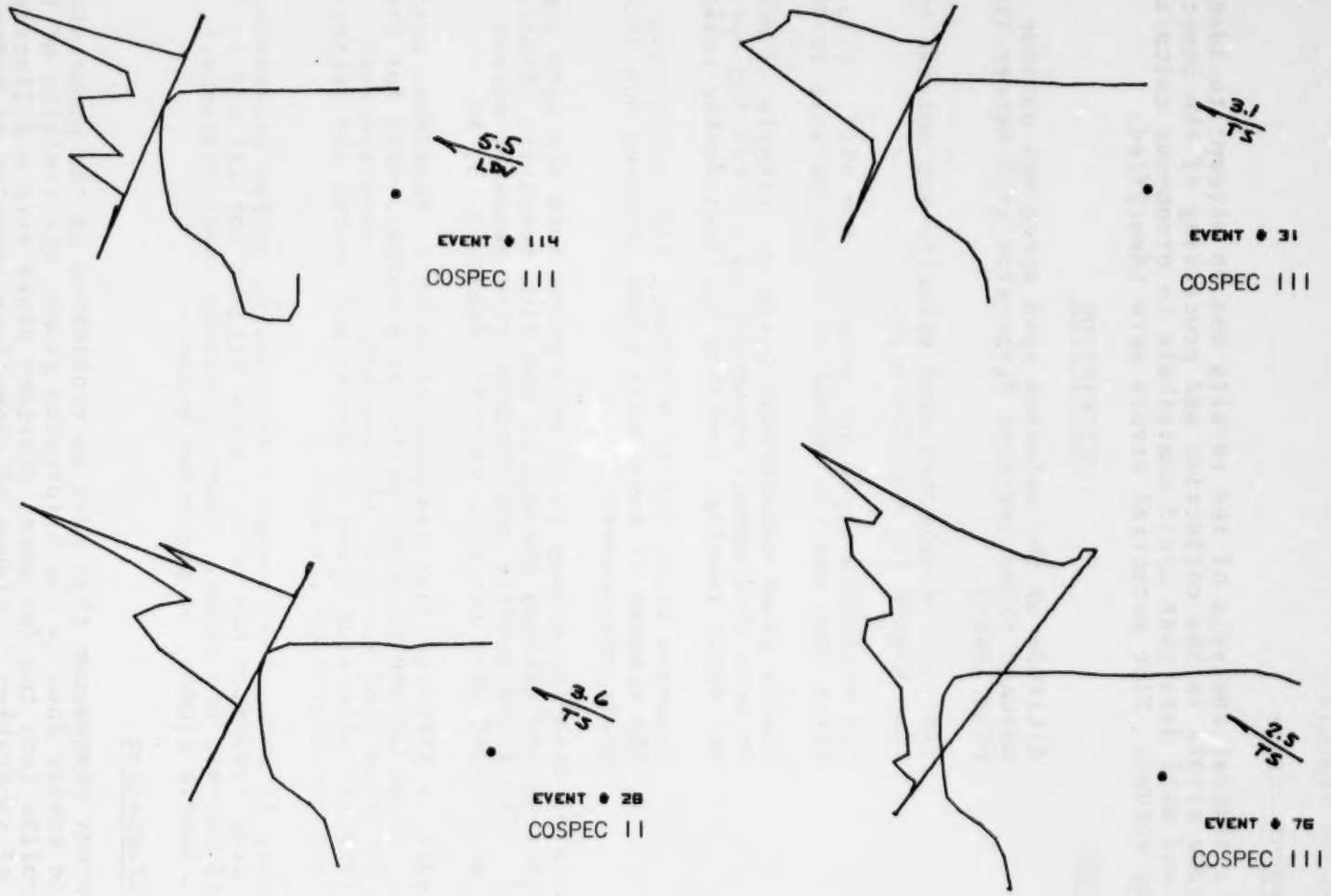

Figure 10. Wind/Road angle > ±50° plumes (Error code c)

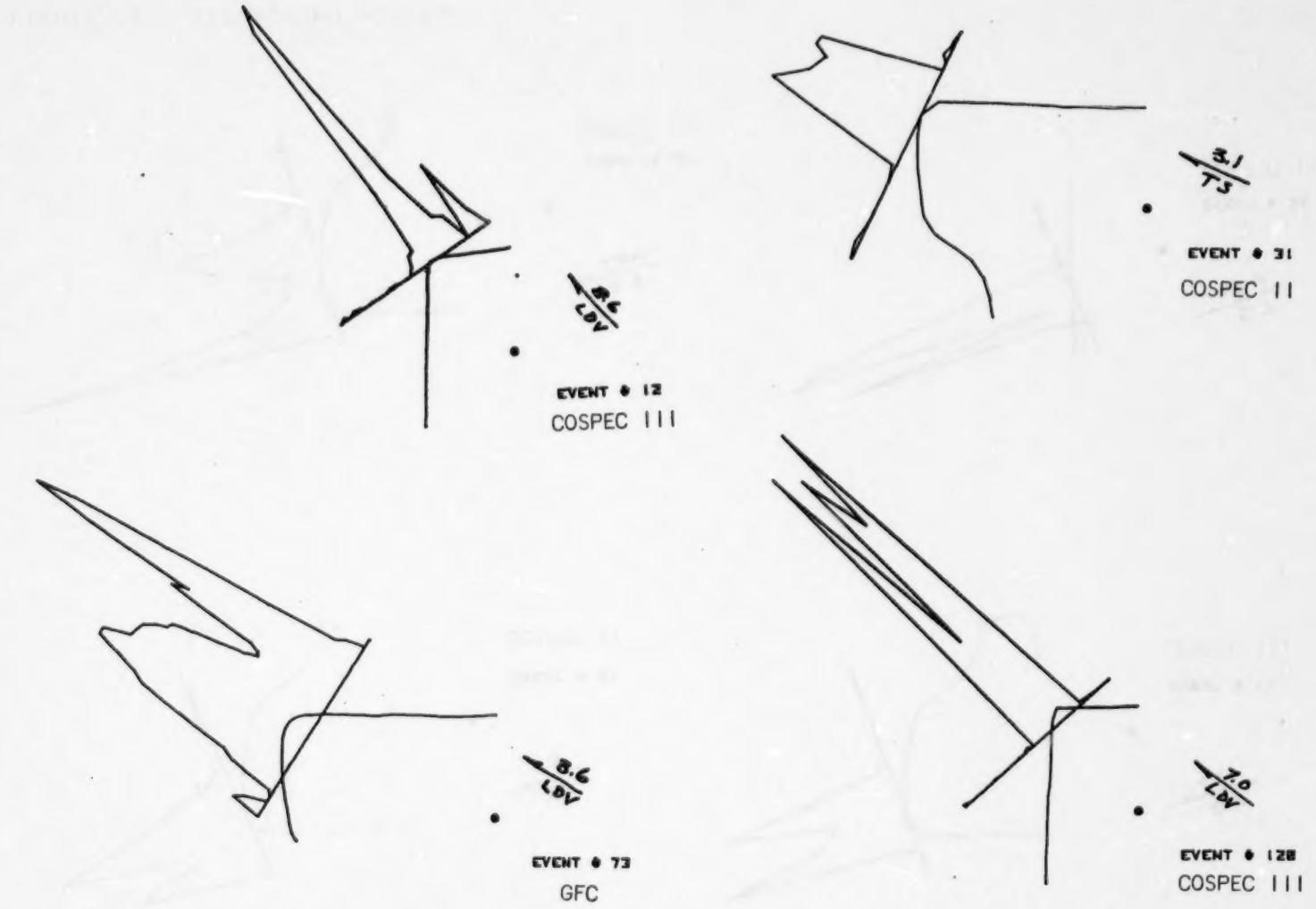

Figure 11. Corner plumes (Error code *e*)

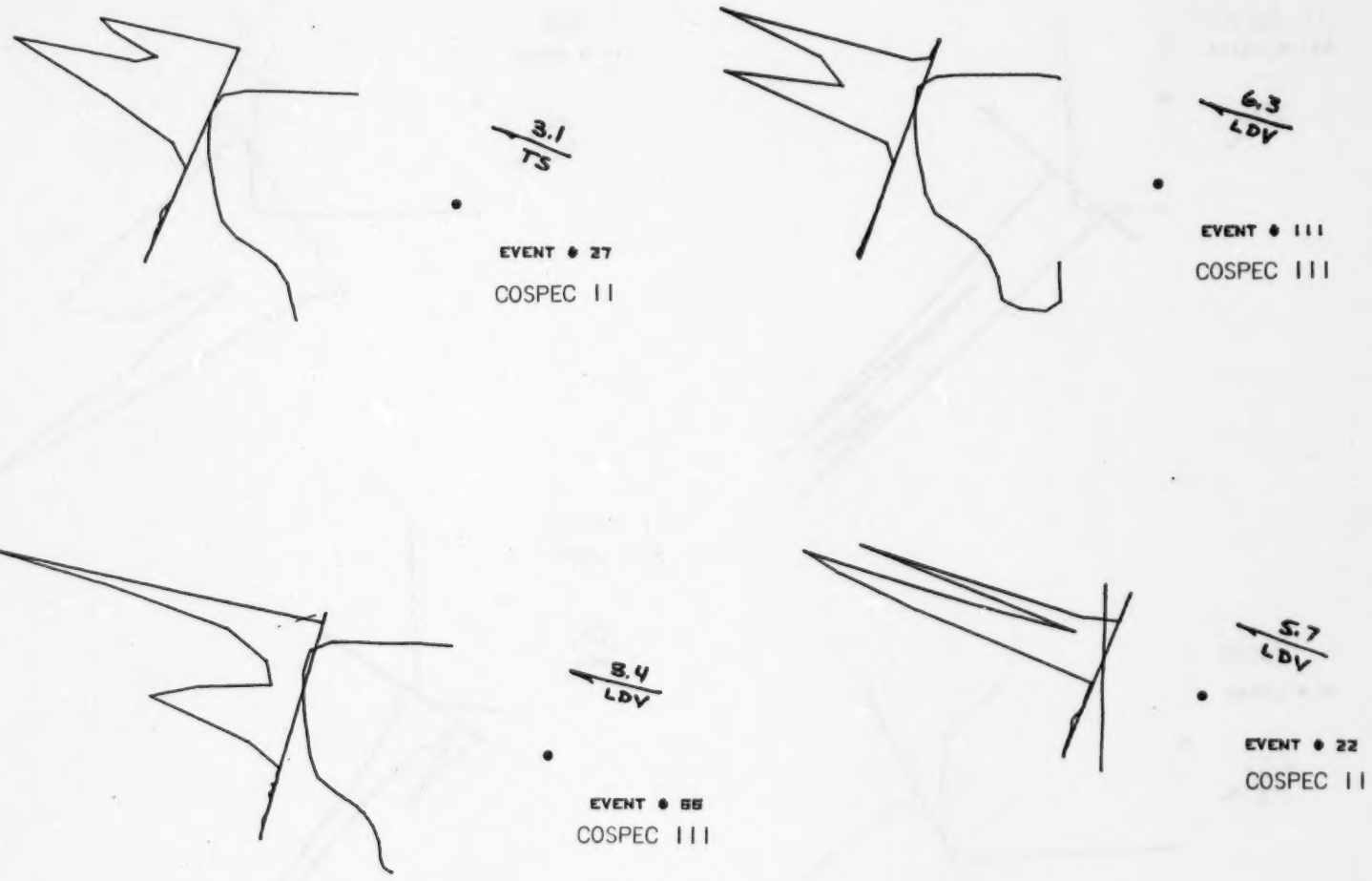

Figure 12. Bifurcated plumes

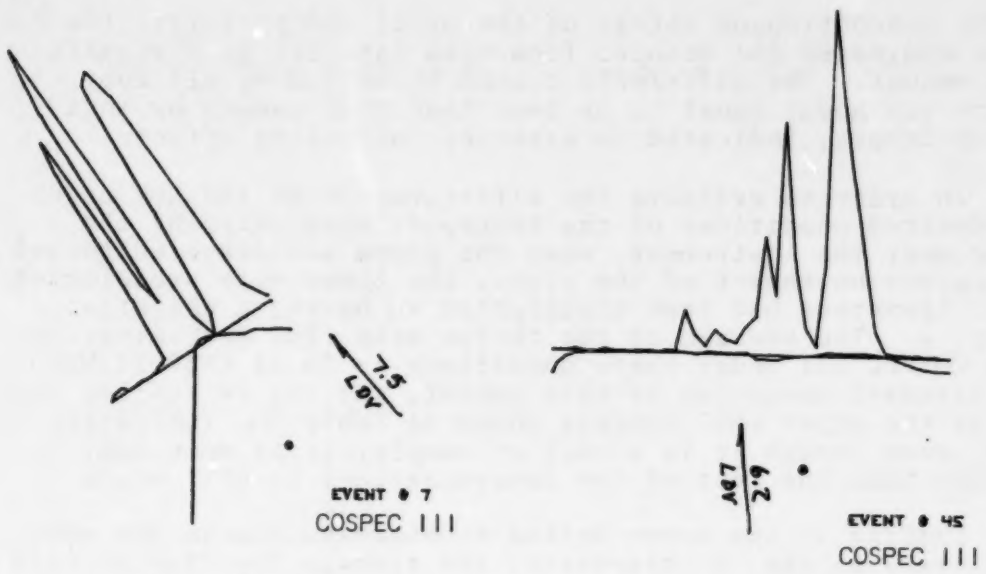

Figure 13. Double plumes

The problem caused by bifurcated plumes is difficulty in discrimination between cases in which the stack emissions have been physically divided by the mechanics of buoyant gases and those in which a plume has actually been measured twice. Because of velocity and/or directional shear, the plume may have separated into multiple parcels that reappear over the traverse route during a single survey.

Plume Sorting

The errors were studied to determine their relative impact on overall average SO_2 Mass Flux. Tables 6, 7, and 8 present COSPEC III and COSPEC II results for all four days with averages, excluding the individual Errors (*a*,*b*,*c*,*d*,*e*); finally, averages excluding all four Errors are given.

The differences in the four-day SO_2 Mass Flux averages caused by excluding these Errors range from -10.9 to +19.6 MT/D. No single Error caused the highest difference consistently, though Errors *c* and *e* usually had more impact than Errors *a* and *b*. Error *c* (orientation of the plume and route) had the largest influence by a slight amount on results obtained from LDV' winds and the second largest effect on TS winds as judged by reduction in the standard deviation of the average, expressed as "%". The *a* error (altitude of wind data) had the greatest influence on TS data, as might be expected because of tethersonde altitude constraints. Because

of the noncontinuous nature of the pibal and profiles, the *b* Error dominated the results from this data set by a significant amount. The difference caused by excluding all four Errors was about equal to or less than that caused by individual Errors, indicated an expected cancelling effect.

In order to evaluate the effectiveness of the LDV under the desired conditions of the transport wind carrying the plume near the instrument, when the plume was directed toward the corner northwest of the plant, the times were preselected. These traverses had been highlighted as having a potential Error, *e*. The average of the twelve mean flux determinations with COSPEC III under these conditions is 70.11 (±37.2%)MT/D. The standard deviation of this subset, ±37.2%, is smaller than any of the other LDV' subsets shown in Table 6, indicating that, even though it is a smaller sample, it is more homogeneous than the rest of the determinations by LDV' winds.

Looking at the seven Method 6 determinations in the same time frame as the *e* traverses, the average SO_2 flux is 66.2 (±8.1%) MT/D. Thus the average of twelve *e* traverses is within 6% of the seven Method 6 determinations -- the best agreement with Method 6 of any subset of the field measurements.

Additional error analyses were performed. Correlations were sought between traverse time, wind speed, and plume width and excessively high flux values; none were found.*

*Note added in review: Millán Millán suggested that error analyses might extend to consideration of "plume aspect", i.e.: Whether or not it was a cohesive or non-cohesive plume, in light of the unstable condition during the study. Such conditions may well require a larger number of profiles in a set to improve the correlation with stack measurements.

TABLE 6. ANALYSIS of RESULTS - LDV' WINDS

TRAVERSES INCLUDED	COSPEC III		COSPEC II	
	NO.	AVG SO_2 FLUX (MT/D)	NO.	AVG SO_2 FLUX (MT/D)
ALL	59	78.9 (±40.9%)	12	63.4 (±28.2%)
ALL EXCEPT *a* ERRORS	56	78.5 (±42.5%)	11	62.8 (±29.8%)
ALL EXCEPT *b* ERRORS	57	79.4 (±41.2%)	10	None - See ALL
ALL EXCEPT *c* ERRORS	51	82.2 (±39.8%)	10	67.8 (±14.8%)
ALL EXCEPT *d* ERRORS	57	77.9 (±41.2%)	10	60.2 (±27.1%)
ALL EXCEPT *e* ERRORS	47	81.2 (±41.7%)	11	61.7 (±28.8%)
ALL EXCEPT *a,b,c,d,e* ERRORS	42	79.6 (±43.6%)	6	61.4 (±18.2%)

Error Codes:

a - altitude of wind data outside limits (±75m)

b - time of wind data outside limits

c - plume axis/traverse route angle outside ±50° limits

d - double plume measured

e - plume traverse on corner

TABLE 7. ANALYSIS of RESULTS - TS WINDS

TRAVERSES INCLUDED	COSPEC III		COSPEC II	
	NO.	AVG SO_2 FLUX (MT/D)	NO.	AVG SO_2 FLUX (MT/D)
ALL	87	64.4 (±37.0%)	31	50.6 (±37.3%)
ALL EXCEPT *a* ERRORS	39	64.6 (±33.4%)	5	70.2 (±27.2%)
ALL EXCEPT *b* ERRORS	87	See ALL	31	See ALL
ALL EXCEPT *c* ERRORS	68	66.9 (±35.7%)	21	53.9 (±37.5%)
ALL EXCEPT *d* ERRORS	84	64.4 (±37.0%)	28	49.6 (±37.4%)
ALL EXCEPT *e* ERRORS	58	66.7 (±36.5%)	20	54.7 (±39.2%)
ALL EXCEPT *a, b, c, d, e* ERRORS	36	65.4 (±39.3%)	5	70.2 (±27.2%)

Error Codes:

a - altitude of wind data outside limits (±75m)

b - time of wind data outside limits

c - plume axis/traverse route angle outside ±50° limits

d - double plume measured

e - plume traverse on corner

TABLE 8. ANALYSIS of RESULTS - PB WINDS

TRAVERSES INCLUDED	COSPEC III		COSPEC II	
	NO.	AVG SO_2 FLUX (MT/D)	NO.	AVG SO_2 FLUX (MT/D)
ALL	30	68.4 (±38.9)	11	51.7 (±32.0%)
ALL EXCEPT *a* ERRORS	31	None -- See ALL	3	None -- See ALL
ALL EXCEPT *b* ERRORS	9	63.9 (±18.2%)	3	42.1 (±13.4%)
ALL EXCEPT *c* ERRORS	28	68.5 (±40.3%)	10	53.0 (±31.8%)
ALL EXCEPT *d* ERRORS	28	68.4 (±40.0%)	9	51.8 (±35.2%)
ALL EXCEPT *e* ERRORS	24	66.5 (±38.3%)	11	See ALL
ALL EXCEPT *a, b, c, d, e* ERRORS	6	64.3 (±21.5)	2	40.8 (±17.9%)

Error Codes:

a - altitude of wind data outside limits (±75m)

b - time of wind data outside limits

c - plume axis/traverse route angle outside ±50° limits

d - double plume measured

e - plume traverse on corner

SECTION 6

COMPARISON of RESULTS

TIME-AVERAGED RESULTS

The COSPEC III results were chosen for comparison with the Method 6 data because there was a larger data base for statistical analysis. The sets of values were first prepared by averaging over common time intervals. The 20-minute Method 6 runs defined the time intervals for which COSPEC III fluxes were averaged; two to five traverses were averaged for each Method 6 test. The 20-minute average are tabulated in Tables 9, 10, and 11. There are seven to eighteen resulting sets of 20-minute averages, depending on which of the four sets of wind data were used.

Similarly, 60-minute averages were calculated for three to thirteen COSPEC III traverses. These are listed in Tables 12 and 13. There are seven to twelve resulting sets of 60-minute averages, depending on which wind data were used. No 60-minute averages were done for the pibal wind data because of insufficient data.

(These averages were calculated without making any correction for moisture in the stack sampling SO_2 mass fluxes in this first-order analysis.)

These five tables reveal considerable variability in the SO_2 mass flux results with respect to the three wind measuring systems. The individual 20-minute remote sensing averages differ up to +95%. The greatest differences occur in the LDV' data (reprocessed), followed by the tethersonde (TS) results. The pibal (PB) results have the best agreement with Method 6 among the 20-minute averages. The range of the percentage differences for each data set (after a single worst value was discarded) are summarized below:

	DIFFERENCES BETWEEN REMOTE and STACK SO_2 FLUXES	
DATA SET	20-Minute Averages	60-Minute Averages
COSPEC III/LDV'	+42%, -45%	+24%, -19%
COSPEC III/TS	+31%, -54%	+18%, -20%
COSPEC III/PB	+23%, -17%	-- --

TABLE 9. COMPARISON of RESULTS
COSPEC III/LDV' vs METHOD 6 - 20-MINUTE AVERAGES

DATE AUG 1976	REMOTE SENSING			STACK SAMPLING		
	TIME (MDT)	NO. OF TRAVERSES	SO_2 FLUX (MT/D)	TIME (MDT)	RUN NO.	SO_2 FLUX (MT/D)
3	1020-1032	3		1020-1040	1	70.8
	1057-1112	2		1053-1113	2	63.4
	1143-1150	2		1125-1145	3	47.0
4	0856-0916	4		0851-0911	5	67.9
	0925-0942	4		0923-0943	6	69.4
	1007-1027	4		1005-1025	7	69.0
	1047-1059	3		1041-1101	8	70.5
	1141-1158	3		1143-1203	9	67.7
	1316-1341	3	86.0	1319-1339	10	73.8
5	0924-0937	2	73.0	0912-0932	13	68.0
	0941-1004	4	85.4	0942-1002	14	70.7
	1040-1108	2	58.7	1039-1059	15	75.0
	1100-1132	4	81.7	1105-1125	16	64.8
	1132-1155	3		1131-1151	17	72.6
	1211-1227	2	37.9	1210-1230	18	69.2
	1308-1323	4	122.9	1304-1324	19	67.7
6	0918-0941	4	52.7	0915-0935	21	70.8
	0944-1008	5	55.7	0945-1005	22	63.0
	1057-1120	5	91.2	1056-1116	24	64.3
	1130-1156	5	72.9	1129-1149	25	62.4

TABLE 10. COMPARISON of RESULTS
COSPEC III/TS vs METHOD 6 - 20-MINUTE AVERAGES

DATE AUG 1976	REMOTE SENSING			STACK SAMPLING		
	TIME (MDT)	NO. OF TRAVERSES	SO_2 FLUX (MT/D)	TIME (MDT)	RUN NO.	SO_2 FLUX (MT/D)
3	1020-1032	3		1020-1040	1	70.8
	1057-1112	2		1053-1113	2	63.4
	1143-1150	2		1125-1145	3	47.0
4	0856-0913	3	53.8	0851-0911	5	67.9
	0935-0942	2	82.1	0923-0943	6	69.4
	1007-1027	4	52.8	1005-1025	7	69.0
	1047-1059	3	67.6	1041-1101	8	70.5
	1141-1158	3	56.0	1143-1203	9	67.7
	1321-1341	2	27.5	1319-1339	10	73.8
5	0924-0937	2	82.7	0912-0932	13	68.0
	0941-1008	5	83.0	0942-1002	14	70.7
	1040-1108	2	44.9	1039-1059	15	75.0
	1100-1132	4	66.3	1105-1125	16	64.8
	1132-1155	3	93.2	1131-1151	17	72.6
	1211-1227	2	31.9	1210-1230	18	69.2
	1308-1323	4	69.6	1304-1324	19	67.7
6	0918-0941	4	49.5	0915-0935	21	70.8
	0944-1001	4	56.0	0945-1005	22	63.0
	1057-1120	5	84.3	1056-1116	24	64.3
	1130-1151	4	52.9	1129-1149	25	62.4

TABLE 11. COMPARISON of RESULTS
COSPEC III/PB vs METHOD 6 - 20-MINUTE AVERAGES

DATE AUG 1976	REMOTE SENSING			STACK SAMPLING		
	TIME (MDT)	NO. OF TRAVERSES	SO_2 FLUX (MT/D)	TIME (MDT)	RUN NO.	SO_2 FLUX (MT/D)
3	1020-1035	3	67.8	1020-1040	1	70.8
4	1316-1314	4	61.5	1319-1339	10	73.8
	1444-1501	4	76.3	1500-1520	12	71.9
5	0924-0948	4	83.3	0912-0932	13	68.0
	1036-1044	2	38.0	1039-1059	15	75.0
	1121-1138	3	63.4	1105-1125	16	64.8
6	0947-1001	3	53.1	0945-1005	22	63.0

TABLE 12. COMPARISON of RESULTS
COSPEC III/LDV' vs METHOD 6 - 60-MINUTE AVERAGES

DATE AUG 1976	REMOTE SENSING			STACK SAMPLING		
	TIME (MDT)	NO. OF TRAVERSES	SO_2 FLUX (MT/D)	TIME (MDT)	RUN NO.	SO_2 FLUX (MT/D)
3	0936-1035	4		1020-1040	1	70.8
	1047-1150	5		1053-1145	2,3	55.2
	1103-1159	5		1053-1159	2,3	55.2
4	0856-0959	10		0856-0942	5,6	68.7
	1001-1059	11		1005-1101	7,8	69.8
	1052-1154	5		1041-1203	8,9	69.1
	1444-1543	6	79.9	1500-1520	12	71.9
5	0924-1004	7	78.0	0912-1002	13,14	69.4
	1036-1132	6	82.0	1039-1125	15,16	69.9
	1126-1227	3	57.2	1131-1230	17,18	70.9
6	0918-1008	10	57.2	0915-1005	21,22	66.9
	1033-1135	13	75.5	1015-1116	23,24	61.1
	1057-1156	12	79.3	1056-1149	24,25	63.4

TABLE 13. COMPARISON of RESULTS
COSPEC III/TS vs METHOD 6 - 60-MINUTE AVERAGES

DATE AUG 1976	REMOTE SENSING			STACK SAMPLING		
	TIME (MDT)	NO. OF TRAVERSES	SO_2 FLUX (MT/D)	TIME (MDT)	RUN NO.	SO_2 FLUX (MT/D)
3	0936-1035	4	-	1020-1040	1	70.8
	1047-1150	5	-	1053-1145	2,3	55.2
	1103-1159	5	-	1053-1159	2,3	55.2
4	0856-0959	6	69.1	0856-0942	5,6	68.7
	1001-1059	11	55.7	1005-1101	7,8	69.8
	1052-1154	5	62.1	1041-1203	8,9	69.1
	1257-1347	4	43.3	1319-1339	10	73.8
5	0924-1023	11	77.7	0912-1002	13,14	69.4
	1036-1138	7	67.7	1039-1125	15,16	69.9
	1126-1227	7	76.3	1131-1230	17,18	70.9
	1308-1354	7	71.2	1304-1403	19,20	66.1
6	0918-1001	9	55.8	0915-1005	21.22	66.9
	1033-1135	13	72.0	1015-1116	23,24	61.1
	1057-1151	11	68.1	1056-1149	24,25	63.4

The LDV' wind data corrected most of the bias, which would have been part of the LDV data set. However, the tethersonde (TS) results have generally better agreement with the stack sampling values, and the pibal (PB) results are an improvement on all three other wind measuring systems for 20-minute averages.

MEANS and DIFFERENCES

Further analysis of the 20-minute and 60-minute averages elucidated the relative accuracy of the remote sensing mass fluxes. In this simple, first-order analysis, the means of the time-averaged data were calculated; the percent differences from the stack sampling averages over the same time period were also figured. These means reduce all of the results to single values; they represent seven to twelve hours of measurements or 25 to 75 traverses.

The results of this analysis are tabulated in Tables 14 and 15. These two tables offer the most succinct summary of the findings of this study. By comparing the two columns of SO_2 mass flux numbers and studying the third column of percent differences it is clear that:

- The LDV' wind data were a significant improvement over LDV values, showing agreement to the reference method within +7.6% (and 6% for winds over the instrument).
- The TS wind data had negative differences up to -9.6%.
- The PB showed the closest agreement (for 20-minute averages only) at +1.0%.

TABLE 14. MEANS and DIFFERENCES of 20-MINUTE AVERAGES

	SO_2 MASS FLUX (MT/D)		
	REMOTE	STACK	DIFF. (%)
COSPEC III/LDV'	73.4	68.2	+ 7.6
COSPEC III/TS	62.0	68.6	- 9.6
COSPEC III/PB	70.3	69.6	+ 1.0

TABLE 15. MEANS and DIFFERENCES of 60-MINUTE AVERAGES

	SO_2 MASS FLUX (MT/D)		
	REMOTE	STACK	DIFF. (%)
COSPEC III/LDV'	72.7	67.6	+ 7.5
COSPEC III/TS	65.4	68.1	- 4.0

It is apparent that the three different sets of wind data (LDV', TS, and PB) produced SO_2 mass fluxes in agreement with Method 6 within ±10% when considering long-term (7-12 hour) averages. This reinforces earlier studies[1,7]; individual COSPEC derived flux calculations are not representative of the true value, but time-averaged data are within ±10% of the accepted reference stack sampling method.

The obvious conclusion is that, the longer the averaging time, the better the remote sensing results. Thus, if only 20-minute remote sensing tests of two to five traverses are used, the expected spread in the results would be about ±35%; for 60 minutes of testing (four to thirteen traverses) the results would have a spread of about ±20%. And, if seven to twelve hours of data are gathered (25 to 75 traverses), the difference is reduced to about ±10%.

Further statistical analyses may sharpen the assessment of relative accuracy by expressing the differences between the remote and in-stack methods in terms of error intervals and confidence limits.

WIND MEASUREMENT ACCURACY

The analysis in Section 5 showed the good agreements of LDV' related flux values to Method 6 determinations if the plume being measured by the COSPEC was transported toward the LDV monitoring site. This improved agreement indicates that the conditions in which the COSPEC and LDV are in the same sector as the plume are the best for reliable measurements. These measurements will be improvements of the use of pibal winds.

The reason for the need for the COSPEC and LDV to be close together to produce good results arises from the fact that the LDV is essentially a point monitor of wind velocity aloft, as opposed to pibal, which determines more of a velocity average over an altitude range between readings. If the point measurements (even those of the tethersonde) are not made near the plume, they will not reflect the transport winds in the plume accurately enough under mid-day turbulent conditions. The averaged pibal data thus can do a better job of approximating the average transport conditions, even though they may not be in the same sector as the plume.

The expense of the LDV system would be justified if it could be capable of readily responding to changes in wind direction in a mobile sense. It would be sufficient to have it relocatable and not necessarily capable of measurements while moving.

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